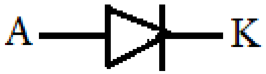
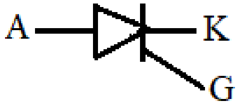
Power Electronics:

Diode



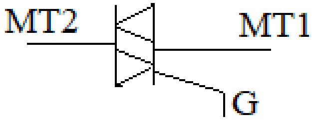
5000 V / 5000 A

Thyrister



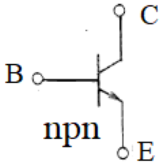
7000 V / 5000 A

Triac



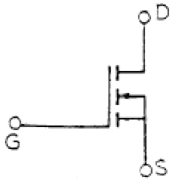
1200 V / 1000 A

BJT



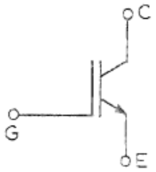
1400 V / 400 A

MOSFET (n channel)



1000 V / 50 A

IGBT



1200 A / 500 V

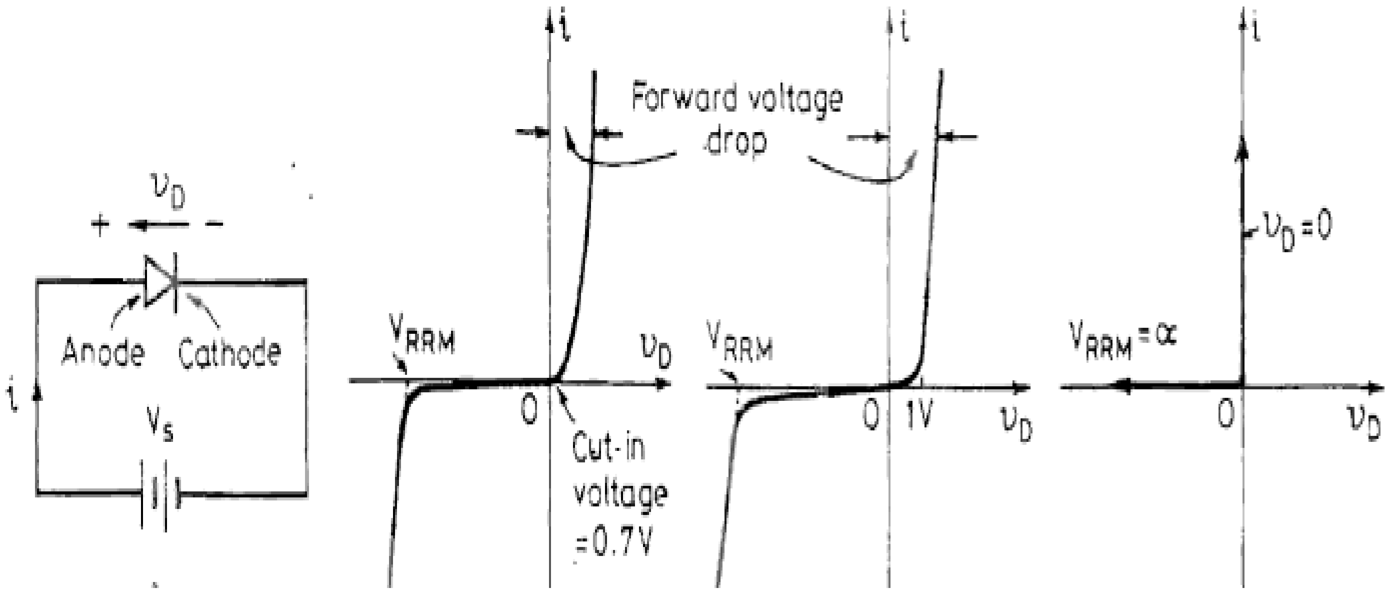
- **Rectifiers**: A rectifier circuit converts ac input voltage into a fixed dc

voltage. The input volt age may be single-phase or three phase. Rectifiers find wide use in electric traction , battery charging, electroplating, electrochemical processing) power supplies, welding and Uninterruptible Power Supply (UPS) systems.

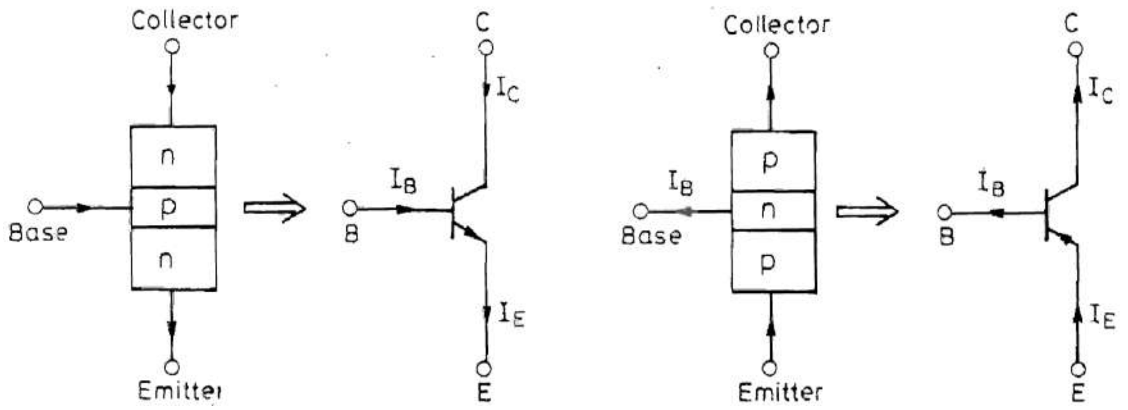
- **Choppers**: A dc chopper converts fixed dc input voltage to a controllable dc output voltage. The chopper circuits require forced, or load, commutation to turn-off the thyristors . For lower power circuits, thyristors are replaced by power transistors. Choppers find ·wide applications in dc drives, subway cars, trolley trucks, battery-driven vehicles etc.

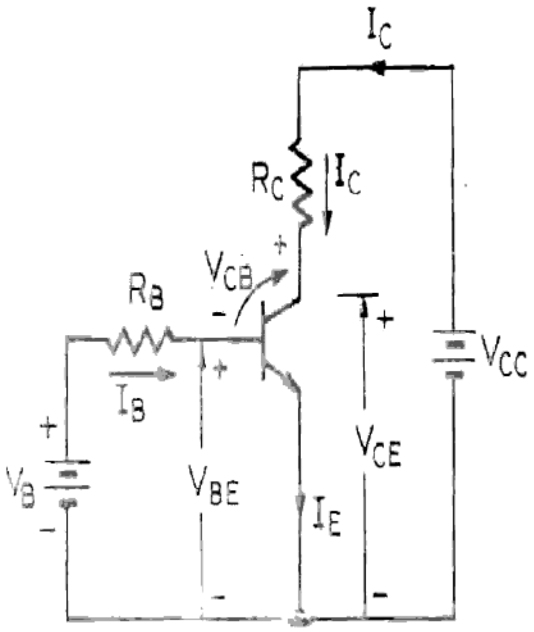
- **Inverters:** An inverter converts fixed dc voltage to a variable ac voltage. The output may be a variable voltage and variable frequency. These converters use forced commutation to turning-off the thyristors. Inverters find wide use in induction-motor and synchronous-motor drives , induction heating, UPS, HVDC transmission, etc.
- **Cycloconverters:** These circuits convert input power at one frequency to output power at a different frequency through one-stage conversion. Line commutation is more common in these converters. *Cycloconverters* are primarily used for slow-speed large ac drives like rotary kiln etc.

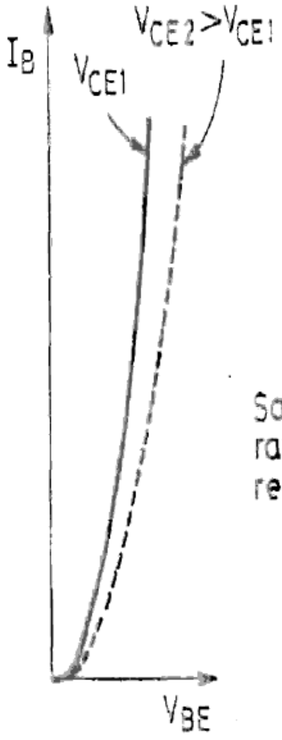
- **Power Diode** is a pn-junction device. A high-power diode, called power diode, is also a pn-junction device but with constructional features somewhat different from a signal diode. Life wise, power transistors also differ in construction from signal transistors.
- When positive terminal of a battery is connected to *p-type* material and negative terminal to n-type material, the *p-n* junction is forward biased.

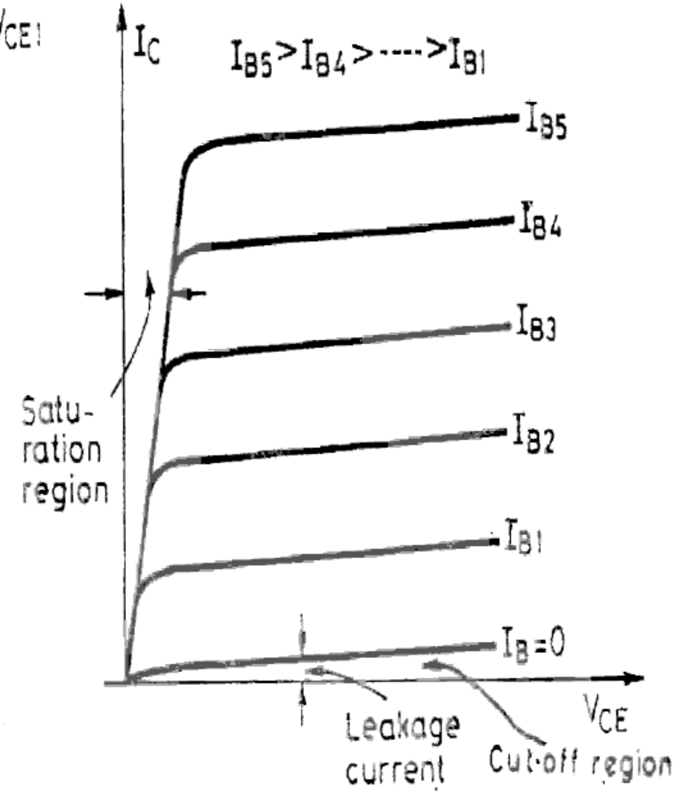


- **Bipolur Junction Transistors(BJT):**

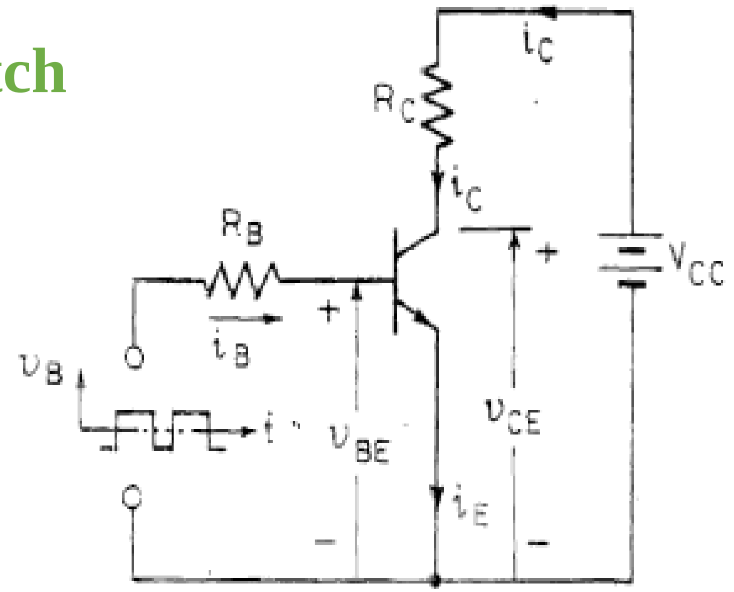


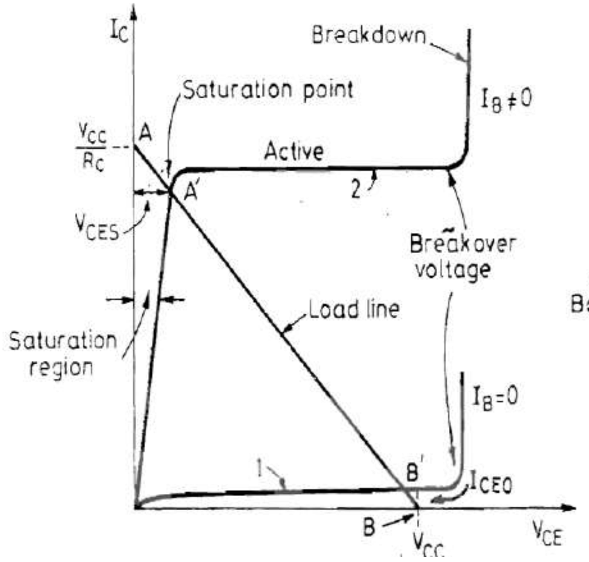


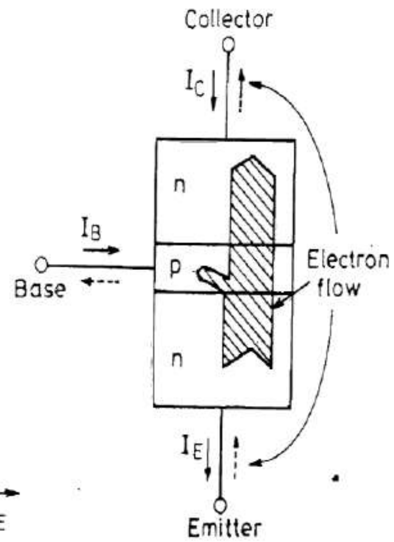


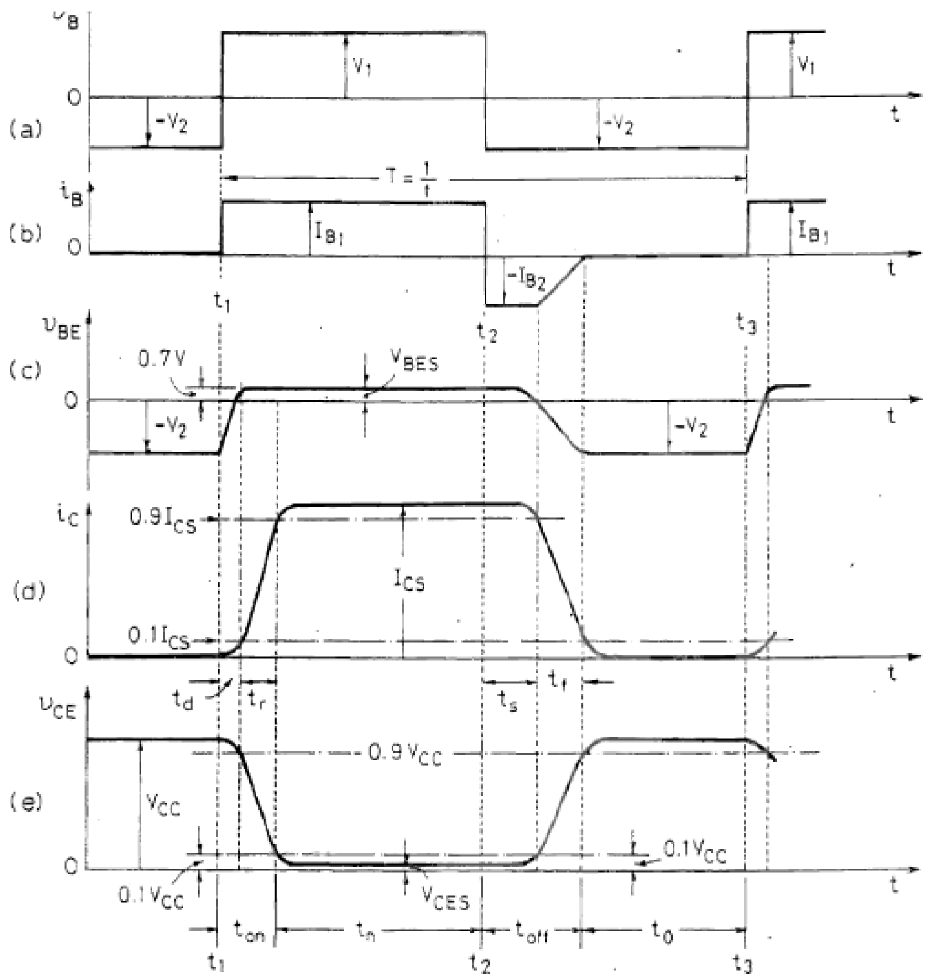


Transistor Switch

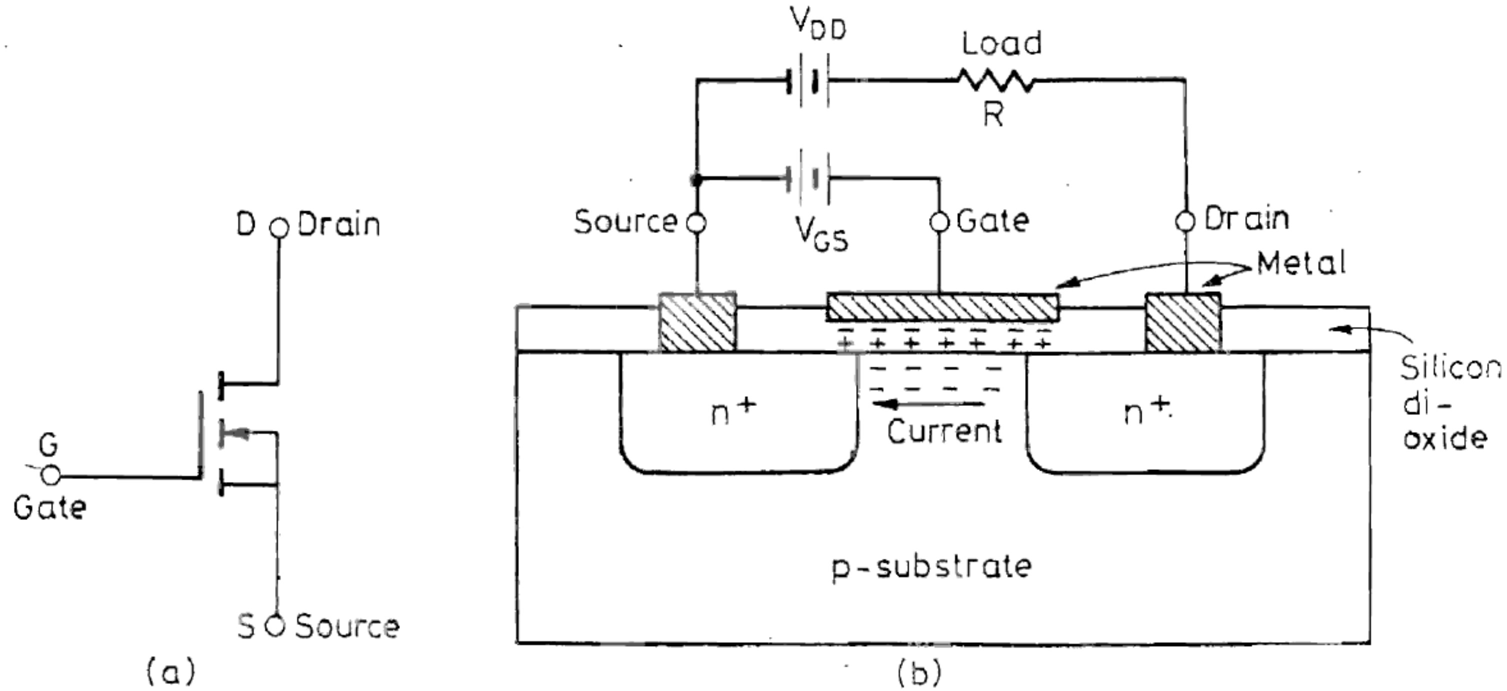




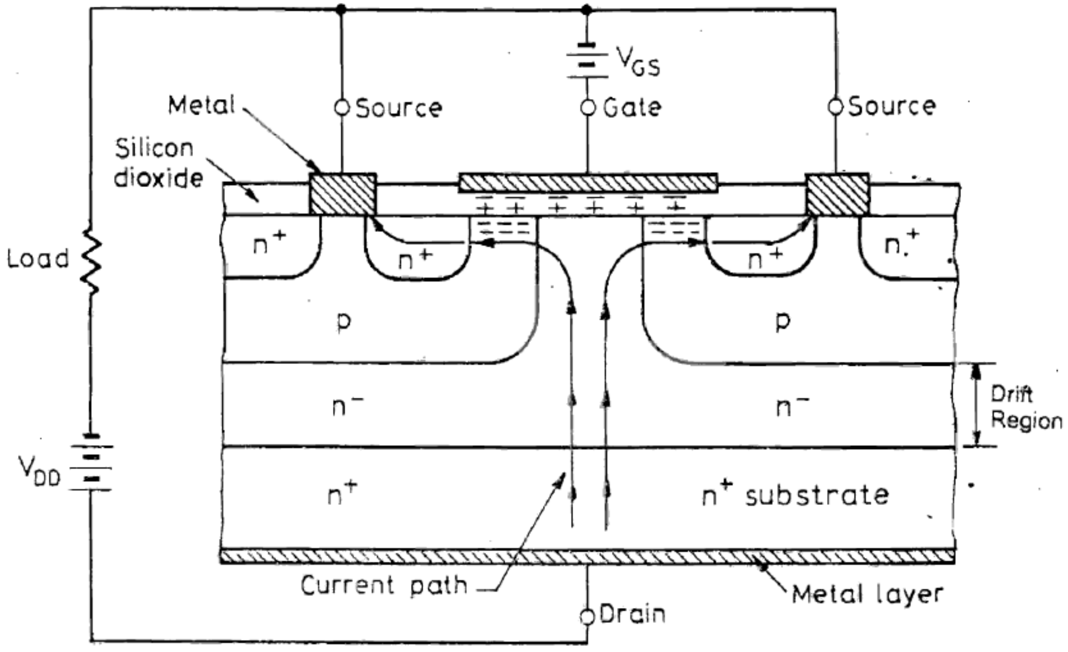


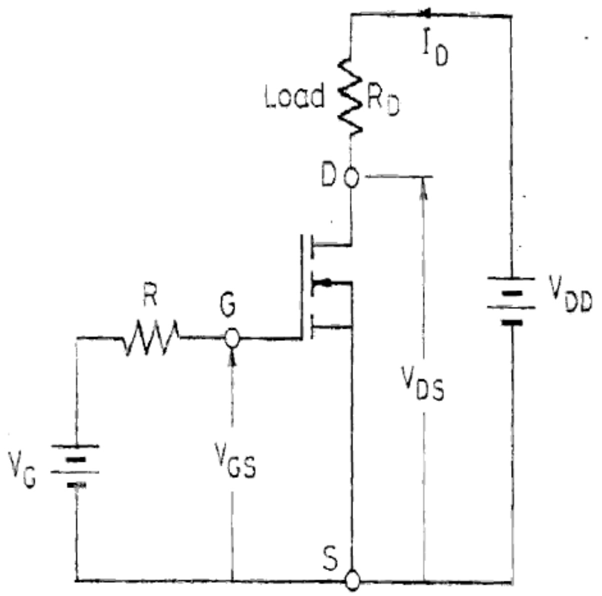


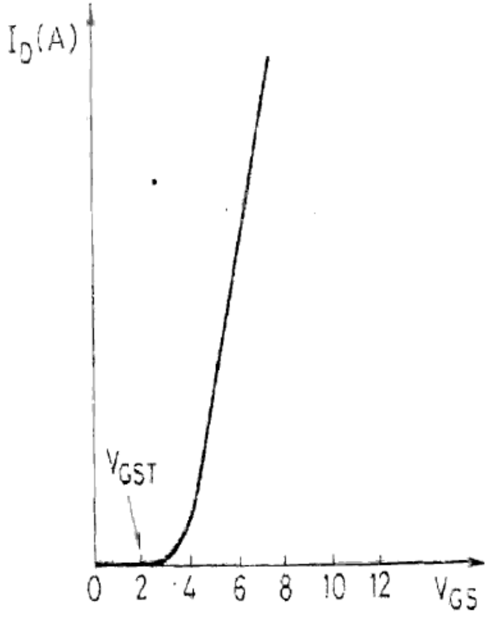
- **MOSFET** is a recent device developed. A power MOSFET has three terminals called drain (D), Source (S) and gate (G). Here arrow indicates the direction of electron flow.
- A BJT is a current controlled device whereas a power MOSFET is a voltage-controlled device. As its operation depends upon the flow of majority carriers only, MOSFET is a unipolar device.



- Power MOSFETs are of two types; n-channel enhancement MOSFET and p-channel enhancement MOSFET. Out of these two types, n-channel enhancement MOSFET is more common because of higher mobility of electrons. When gate circuit is open, junction between *n* region below drain and p-substrate I reverse biased by input voltage V_{DD}. Therefore, no current flows from drain to source and load. When gate is made positive with respect to source, an electric field is established.

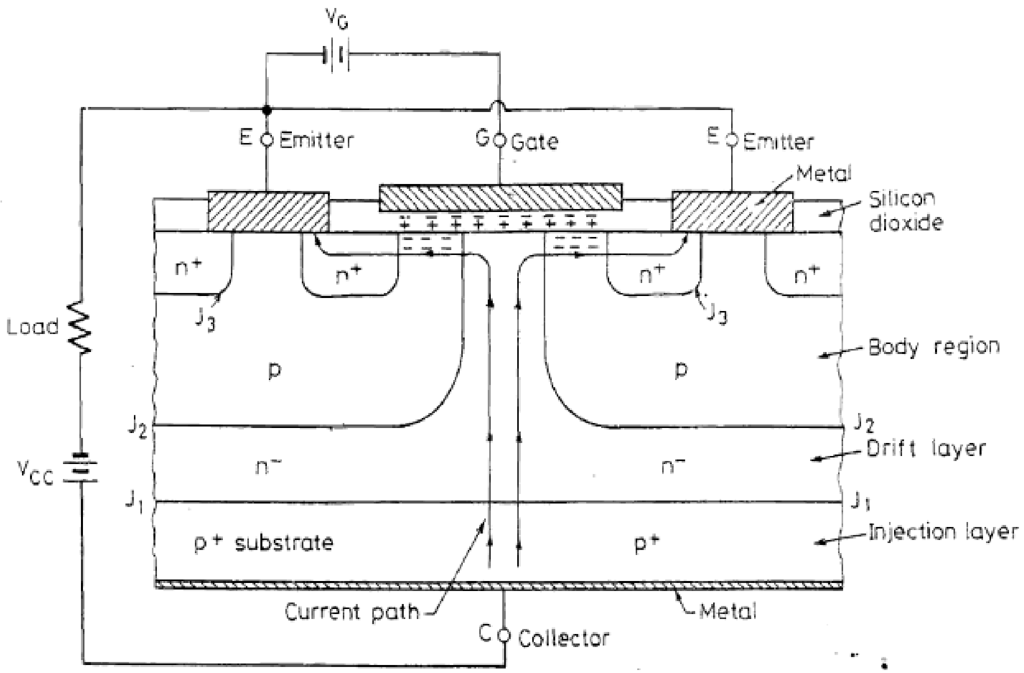


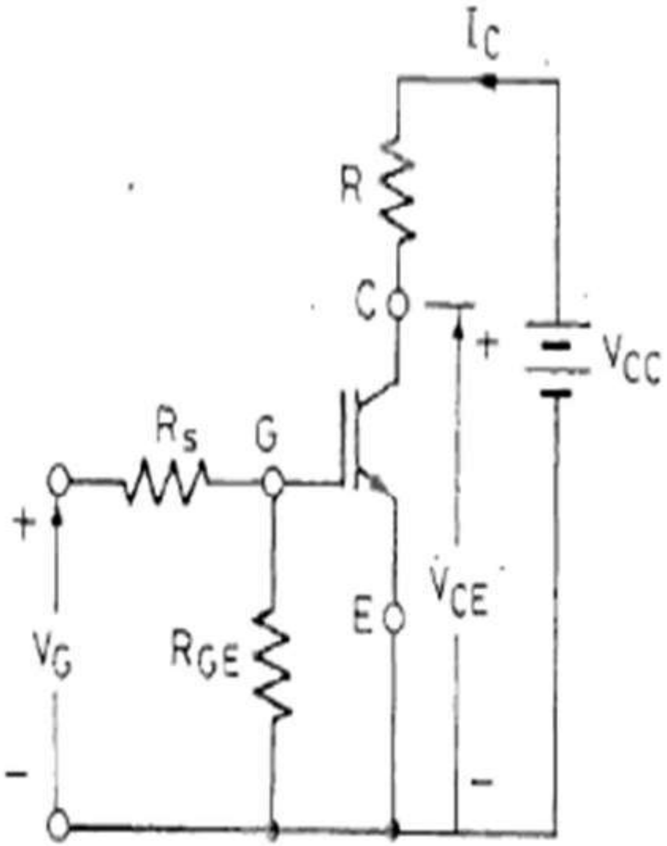


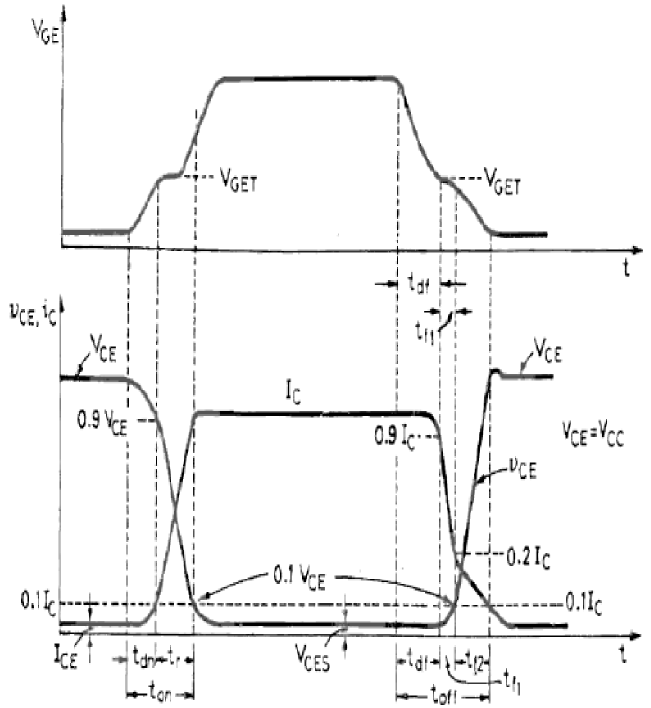


- **Insulated Gate Bipolar Transistor (IGBT)** can be thought as the combination of MOSFET and *pnp* transistor.

When collector is made positive with respect to emitter, IGBT gets forward biased. With no voltage between gate and emitter, junction *J2* are reverse biased; so no current flows from collector to emitter.







- **RC Load:** When switch *S* is closed closed

at t =0, KVL gives:

$$Ri + \frac{1}{C}\int i\,dt = V_s$$

Its Laplace transform is $R\,I(s) + \frac{1}{C}\left[\frac{I(s)}{s} + \frac{q(o)}{s}\right] = \frac{V_s}{s}$

As the initial voltage across C is zero, $q(o) = 0$.

$$I(s)\left[R + \frac{1}{Cs}\right] = \frac{V_s}{s}$$

or

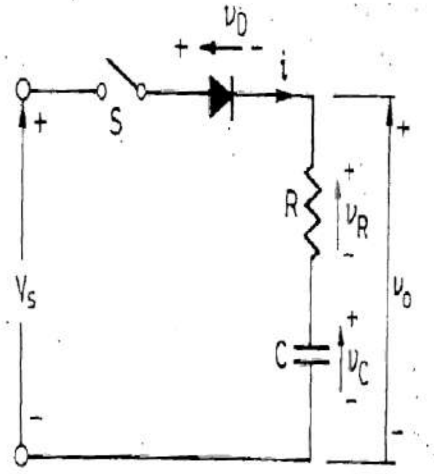
$$I(s) = \frac{CV_s}{RC\left(s + \frac{1}{RC}\right)} = \frac{V_s}{R}\cdot\frac{1}{s + \frac{1}{RC}}$$

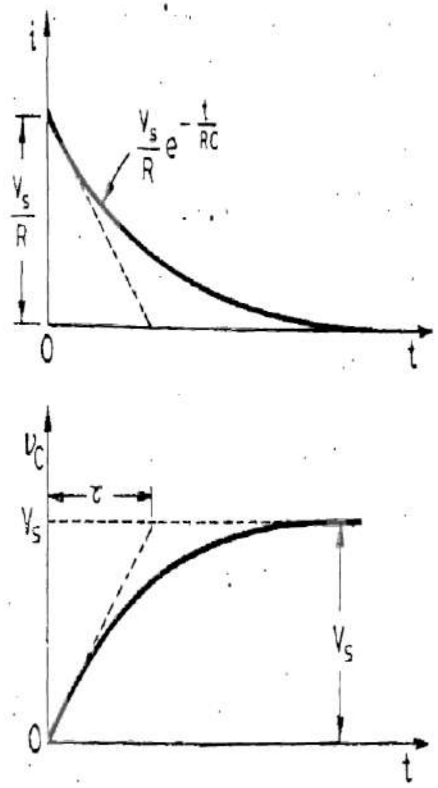
Its Laplace inverse is $i(t) = \frac{V_s}{R}\cdot e^{-t/RC}$

The voltage across capacitor is

$$v_c(t) = \frac{1}{C}\int_0^t i\,dt = \frac{V_s}{RC}\int_0^t e^{-t/RC}\,dt$$

$$= V_s\,(1 - e^{-t/RC}) \qquad = V_s\,(1 - e^{-t/\tau})$$

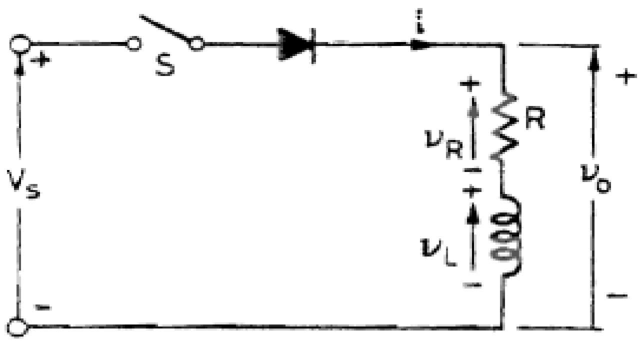


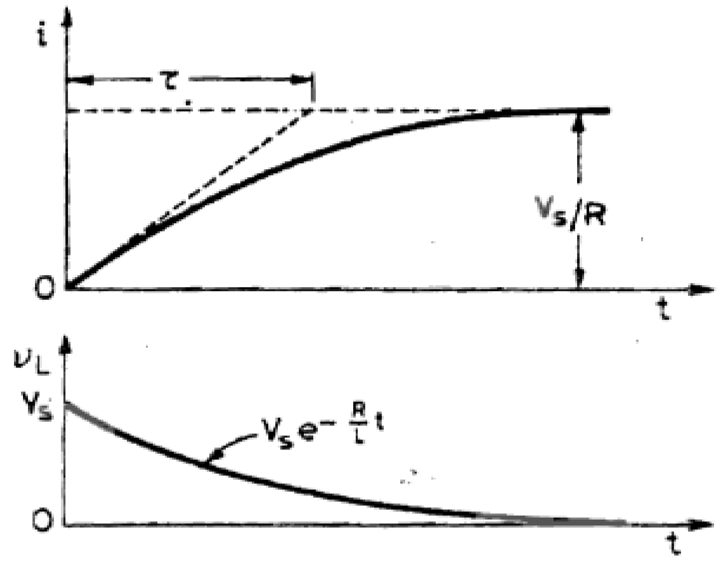


RL Load

When switch S is closed at $t = 0$ in the RL and diode , KVL gives

$$R\,i + L\,\frac{di}{dt} = V_s$$





With initial current in the inductor as zero, the solution gives $i(t) = \frac{V_s}{R}(1 - e^{-\frac{R}{L}t})$

Initial rate of rise of current is

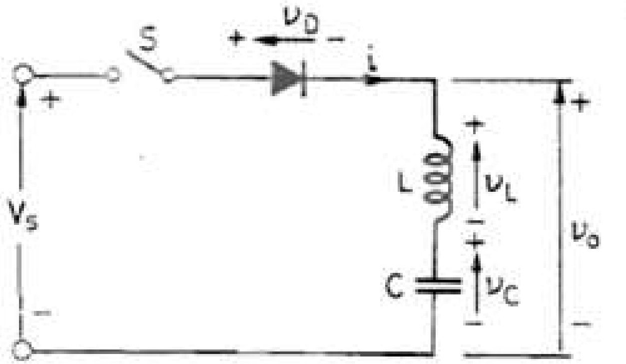
$$\left.\frac{di}{dt}\right|_{t=0} = \left(\frac{V_s}{L} \cdot e^{-\frac{R}{L}t}\right)_{t=0} = \frac{V_s}{L}$$

The voltage across L is $\quad v_L(t) = L\,\frac{di}{dt} = V_s \cdot e^{-\frac{R}{L}t}$

For RL circuit, $\frac{L}{R} = \tau$ is the time constant.

LC Load

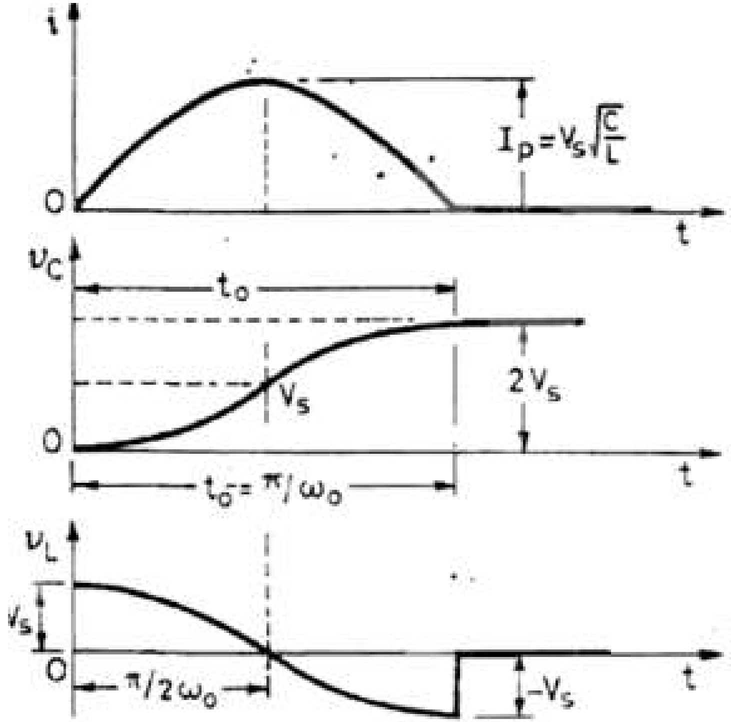
When switch S is closed at $t = 0$,



$$L\frac{di}{dt} + \frac{1}{C}\int i dt = V_s$$

Its Laplace transform is $L\ [s\,I(s) - i(0)] + \dfrac{1}{C}\left[\dfrac{I(s)}{s} + \dfrac{q(0)}{s}\right] = \dfrac{V_s}{s}$

As the circuit is initially relaxed, $i(0) = 0$ and $v_C\,(0) = 0$ or $q(0) = C \cdot v_C(0) = 0$



$\therefore$
$$I(s)\left[sL + \frac{1}{sC}\right] = \frac{V_s}{s}$$

or
$$I(s) = \frac{V_s}{L} \cdot \frac{1}{s^2 + \dfrac{1}{LC}}$$

Let $\omega_0 = \dfrac{1}{\sqrt{LC}}$ · This gives $I(s) = \dfrac{V_s}{L \cdot \omega_0} \cdot \dfrac{\omega_0}{s^2 + \omega_0^2} = V_s \cdot \sqrt{\dfrac{C}{L}} \cdot \dfrac{\omega_0}{s^2 + \omega_0^2}$

Its Laplace inverse is $i(t) = V_s \cdot \sqrt{\dfrac{C}{L}}\ \sin \omega_0 t$

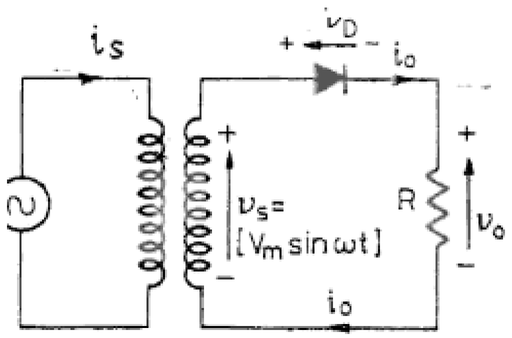
Here $\omega_0 = \dfrac{1}{\sqrt{LC}}$ is called *resonant frequency* of the circuit. Capacitor voltage is given by

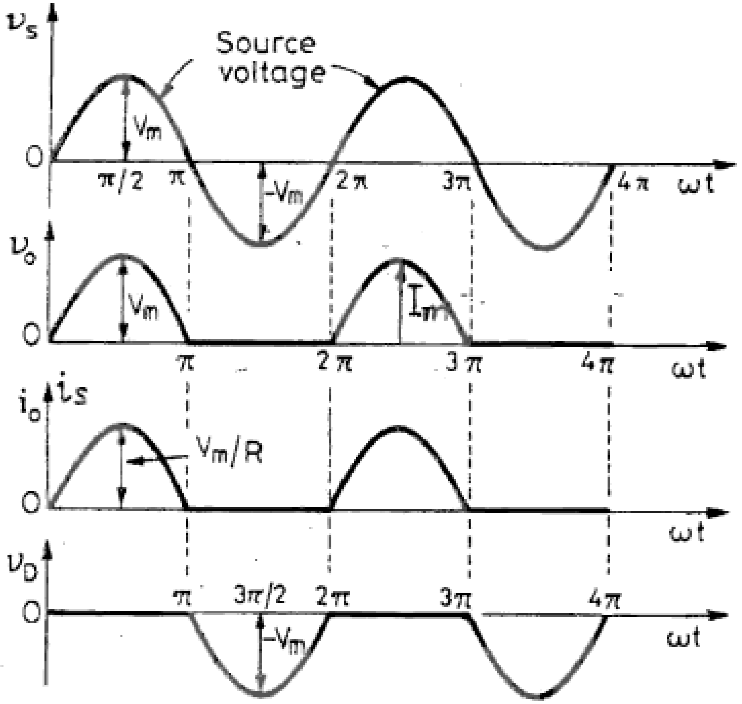
$$v_C(t) = \frac{1}{C}\int_0^t i(t) \cdot dt = \frac{1}{C}\int_0^t V_s \cdot \sqrt{\frac{C}{L}}\ \sin \omega_0 t\ .\ dt \quad = V_s\,(1 - \cos \omega_0 t)$$

Single-Phase Half-wave Rectifier

(a) R load:

During the positive half cycle, diode is forward biased, it therefore conducts from $\omega t = 0 \; to \; \omega t = \pi$





Average value of output (or load) voltage,

$$V_0 = \frac{1}{2\pi}\left[\int_0^{\pi} V_m \sin \omega t \, d(\omega t)\right]$$

$$= \frac{V_m}{2\pi} \left| -\cos \omega t \right|_0^{\pi} = \frac{V_m}{\pi}$$

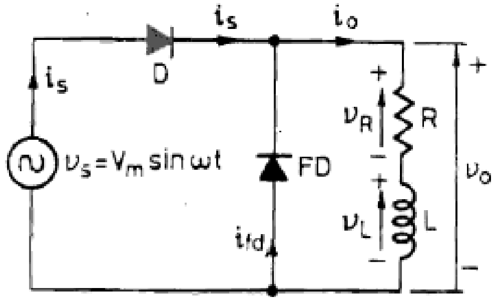
Rms value of output voltage, $V_{or} = \left[\frac{1}{2\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \cdot d(\omega t)\right]^{1/2} = \frac{V_m}{2}$

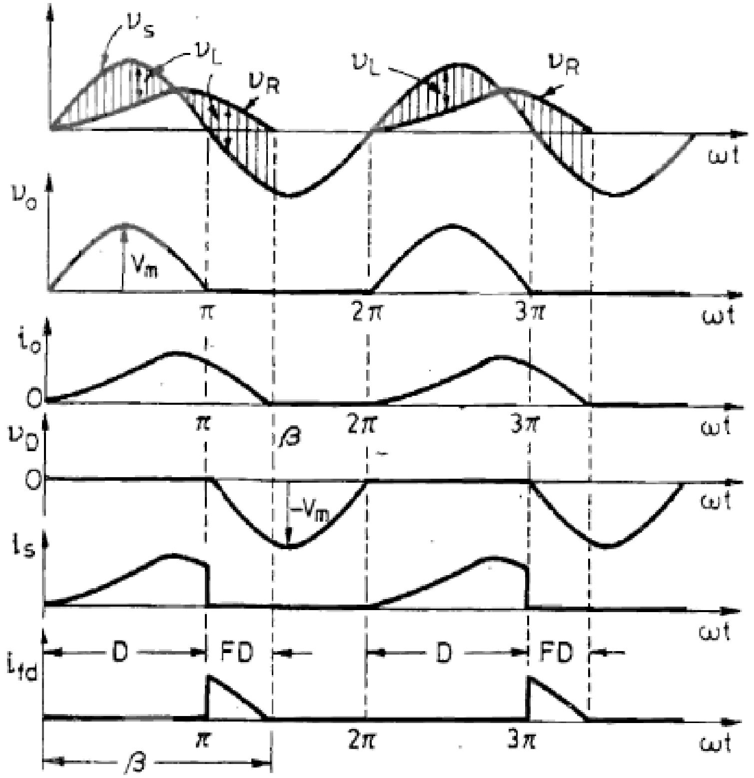
Average value of load current, $I_0 = \frac{V_0}{R} = \frac{V_m}{\pi R}$

Rms value of load current, $I_{or} = \frac{V_{or}}{R} = \frac{V_m}{2R}$

Peak value of load, or diode, current $= \frac{V_m}{R}$

RL load with Freewheeling Diode:





average output voltage, $$V_0 = \frac{1}{2\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t) = \frac{V_m}{\pi}$$

and average load current, $$I_0 = \frac{V_m}{\pi R}$$

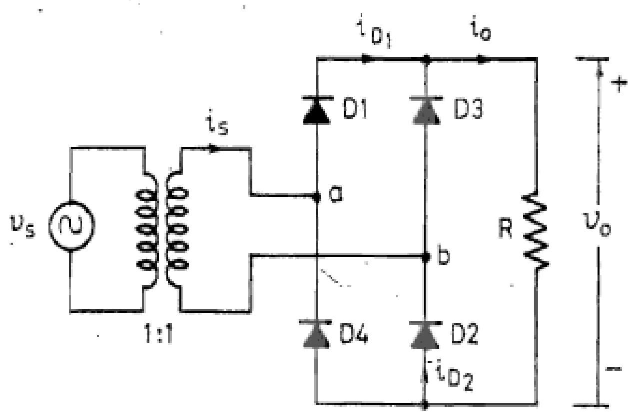
The effects of using freewheeling diode are as under :

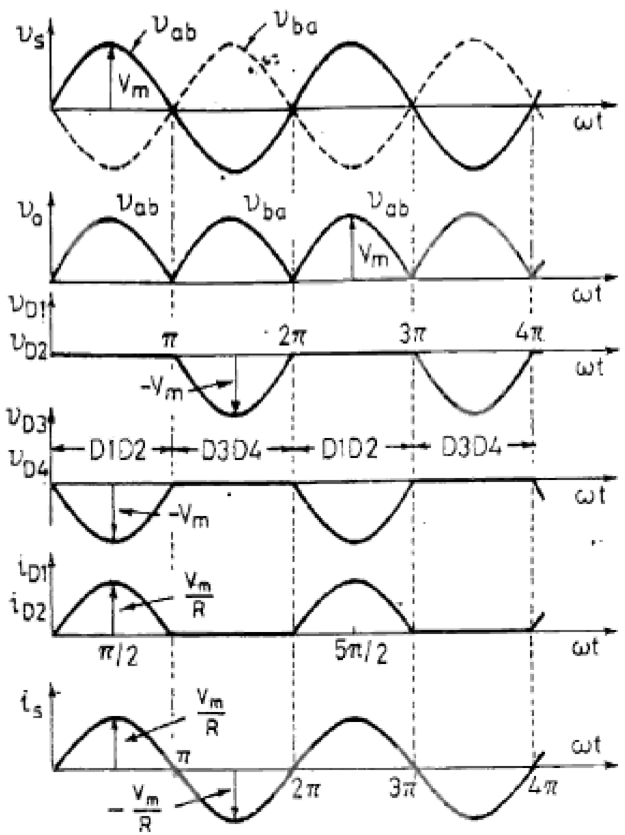
(*i*) It prevents the output (or load) voltage from becoming negative.

(*ii*) As the energy stored in L is transferred to load R through FD, the system efficiency is improved.

(*iii*) The load current waveform is more smooth, the load performance, therefore, gets better.

Single-Phase Full-Wave Diode Bridge Rectifier



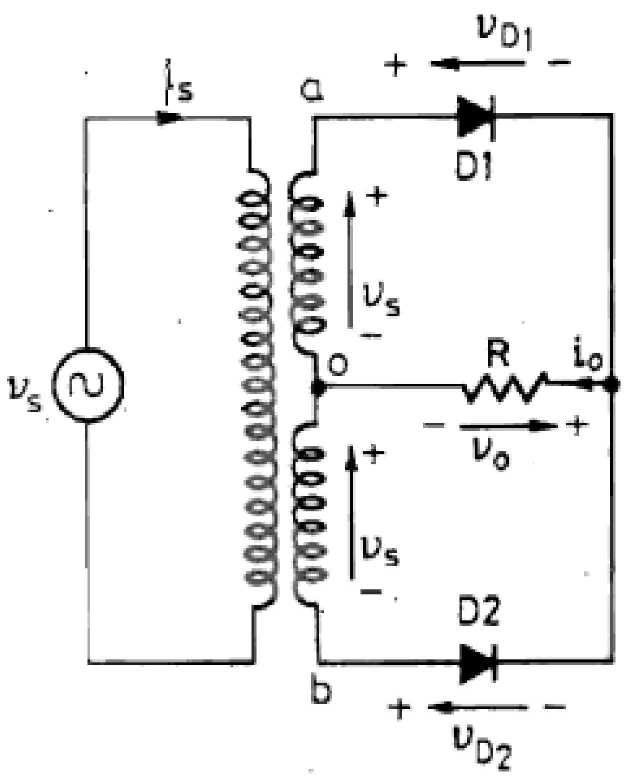


Average value of diode current, $I_{DA} = \frac{1}{2\pi}\int_o^{\pi} I_m \sin \omega t \cdot d(\omega t) = \frac{I_m}{\pi}$

Rms value of diode current, $I_{Dr} = \left[\frac{1}{2\pi}\int_o^{\pi} I_m^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2} = \frac{I_m}{2}$

Peak repetitive diode current, $I_m = \frac{V_m}{R}$

Single-Phase Full-Wave Mid-Point Rectifier



dc output voltage, $V_o = \dfrac{2V_m}{\pi}$

dc output current, $I_0 = \dfrac{2V_m}{\pi R} = \dfrac{2}{\pi} I_m$

Output *dc* power, $P_{dc} = V_o I_o = \dfrac{2V_m}{\pi} . \dfrac{2}{\pi} I_m = \left(\dfrac{2}{\pi}\right)^2 . V_m I_m$

Rms output voltage, $V_{or} = \dfrac{V_m}{\sqrt{2}} = V_s$

Rms output current, $I_{or} = \dfrac{V_m}{\sqrt{2}} \times \dfrac{1}{R} = \dfrac{1}{\sqrt{2}} \left(\dfrac{V_m}{R}\right) = \dfrac{1}{\sqrt{2}} I_m = I_s$

Output *ac* power, $P_{ac} = V_{or} . I_{or} = \dfrac{V_m}{\sqrt{2}} . \dfrac{I_m}{\sqrt{2}} = \dfrac{V_m I_m}{2}$

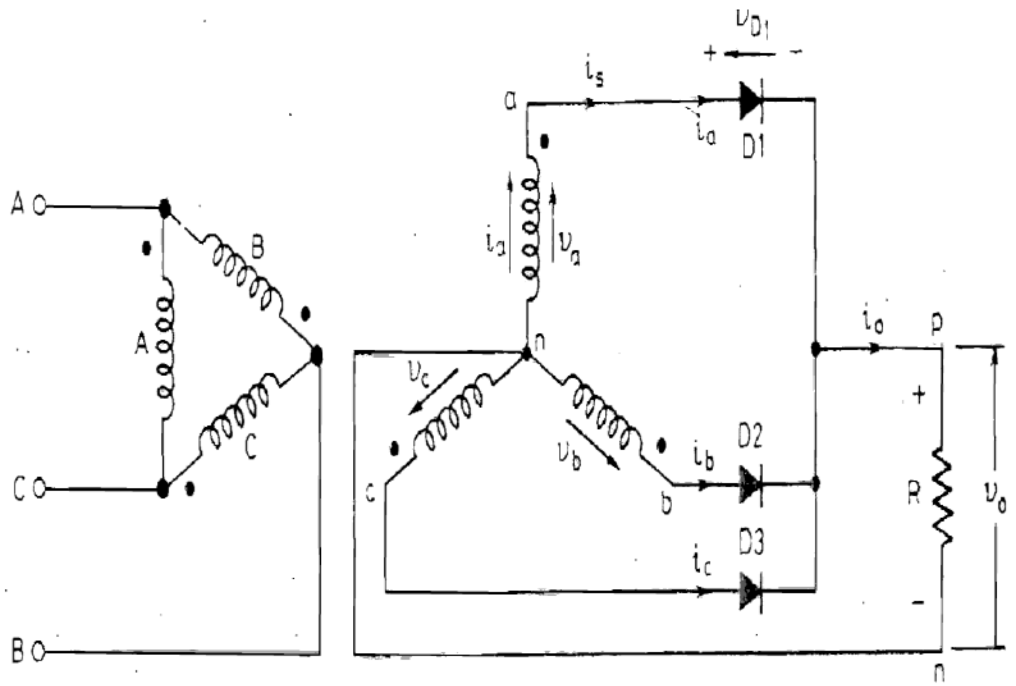
Form factor, $FF = \dfrac{V_{or}}{V_o} = \dfrac{V_m}{\sqrt{2}} . \dfrac{\pi}{2V_m} = \dfrac{\pi}{2\sqrt{2}} = 1.11$

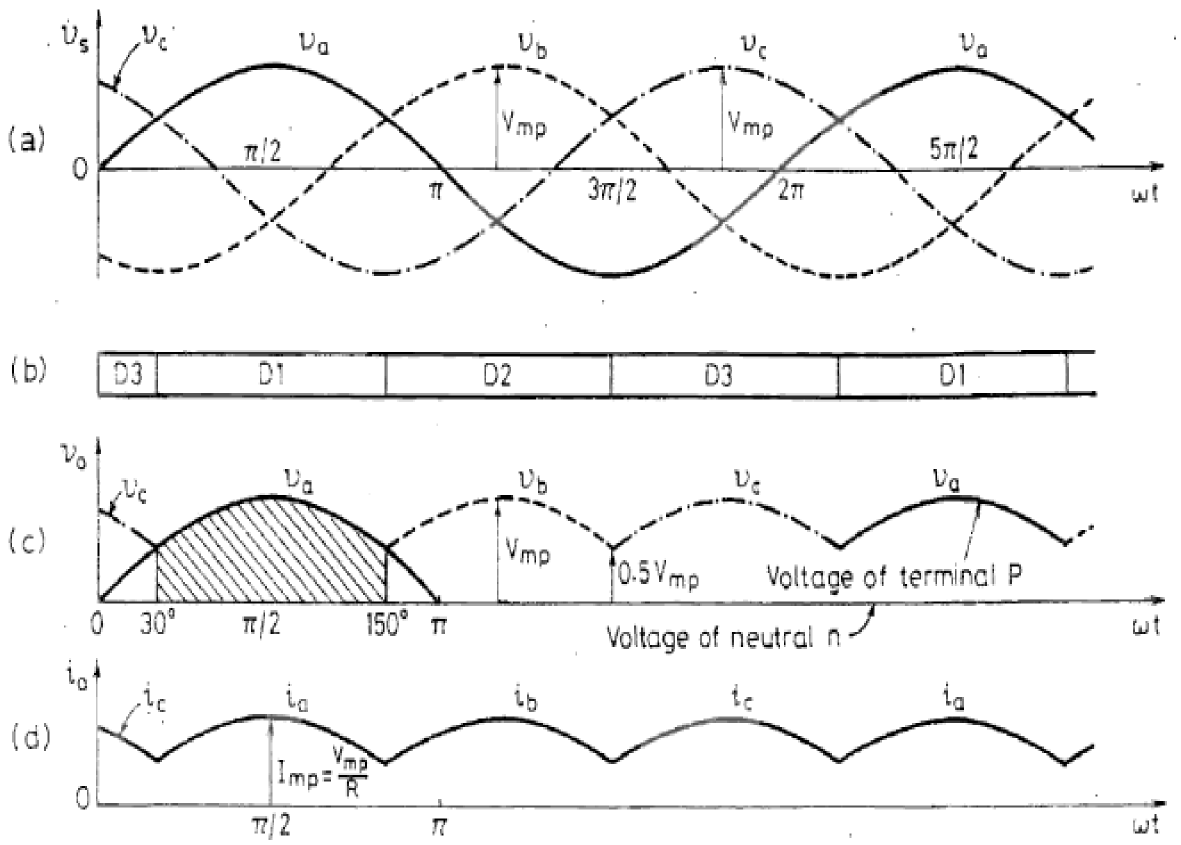
Ripple voltage, $V_r = \sqrt{V_{or}^2 - V_o^2} = \left[\left(\dfrac{V_m}{\sqrt{2}}\right)^2 - \left(\dfrac{2\,V_m}{\pi}\right)^2\right]^{1/2} = 0.3077\,V_m$

Voltage ripple factor, $VRF = \dfrac{V_r}{V_o} = 0.3077\,V_m \times \dfrac{\pi}{2\,V_m} = 0.483$

Also, $VRF = \sqrt{FF^2 - 1} = \sqrt{1.11^2 - 1} = 0.482$

Three-Phase Half-wave Diode Rectifier





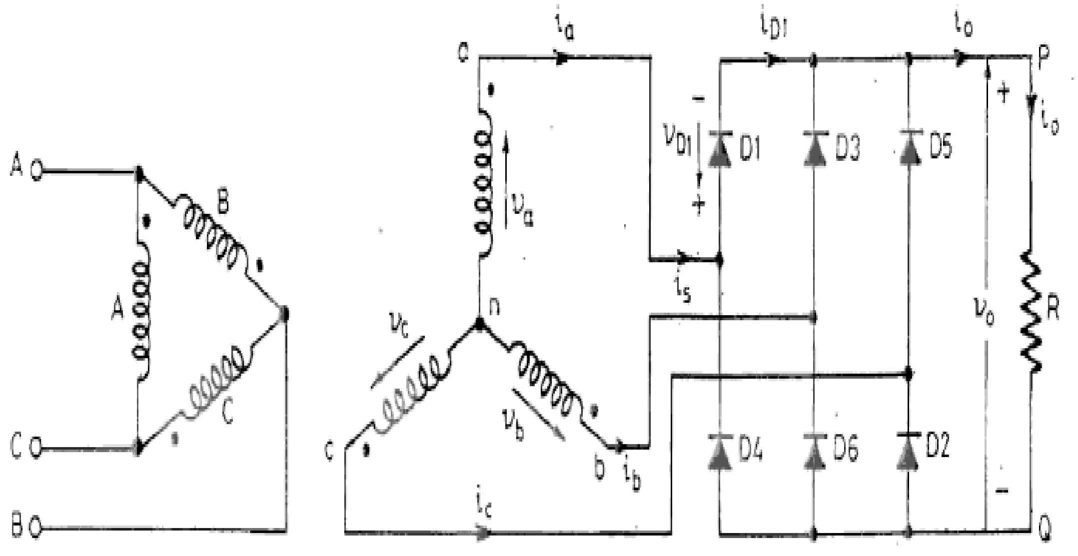
v_a appears from $\omega t = 30°$ to $150°$ in the output voltage waveform; these are, therefore, the limits of integration and periodicity is $120° = 2\pi/3$ radians.

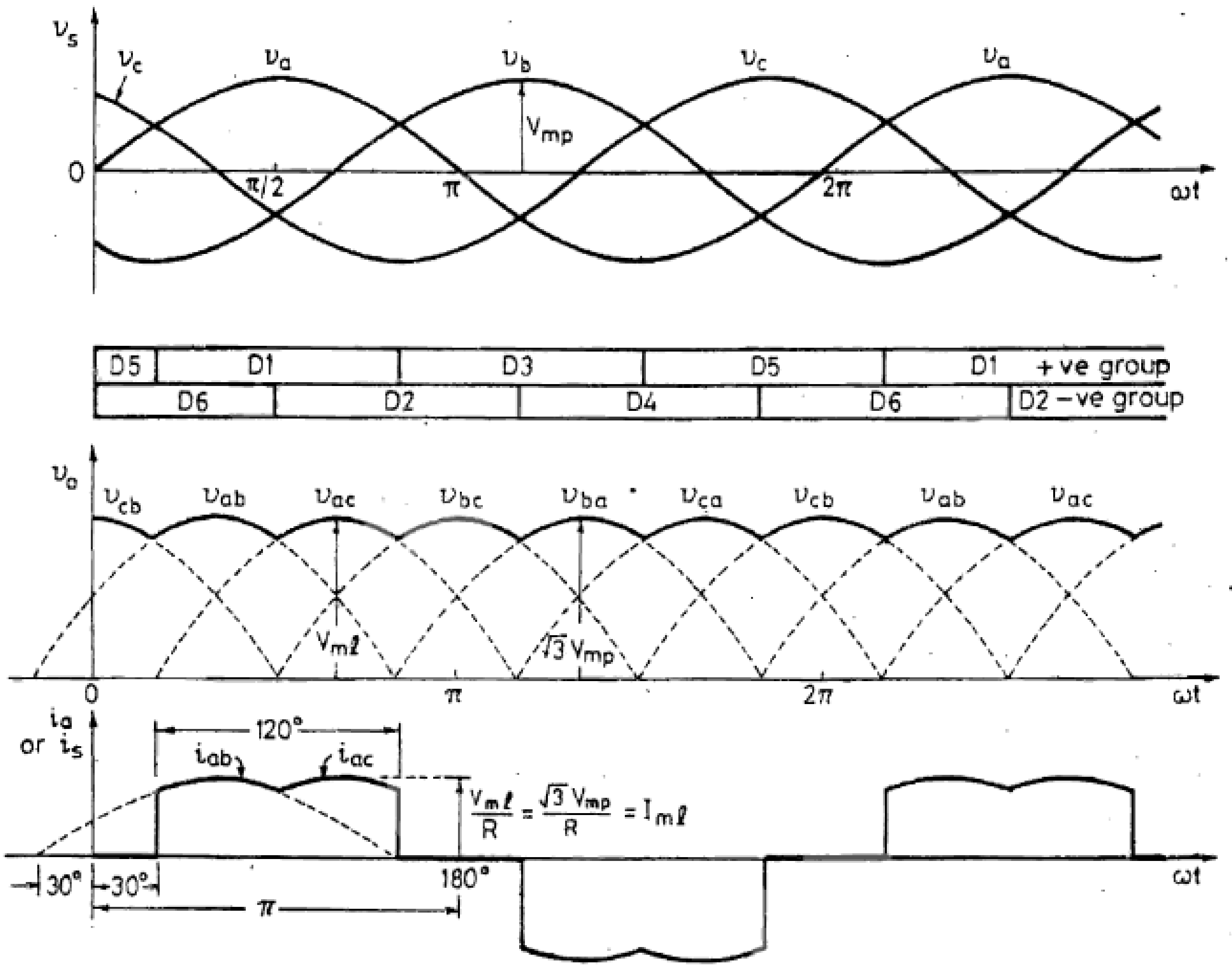
$$\therefore \qquad V_o = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_{mp}\sin\omega t \, . \, d(\omega t) = \frac{3\sqrt{3}}{2\pi} V_{mp} = \frac{3\sqrt{6}}{2\pi} V_{ph} = \frac{3}{2\pi} \, . \, V_{ml}$$

where V_{mp} = maximum value of phase voltage, $V_{mp} = \sqrt{2}\, V_{ph}$

and V_{ml} = maximum value of line voltage, $V_l = \sqrt{3}\, . \, V_{mp} = \sqrt{6}\, . \, V_{ph}$

Three-phase Bridge Rectifier

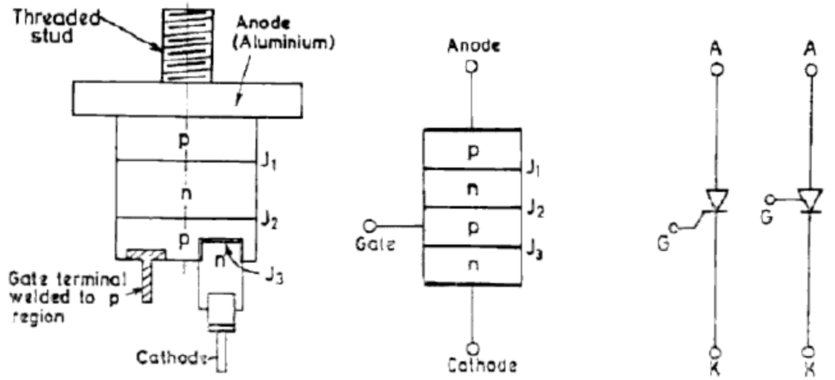


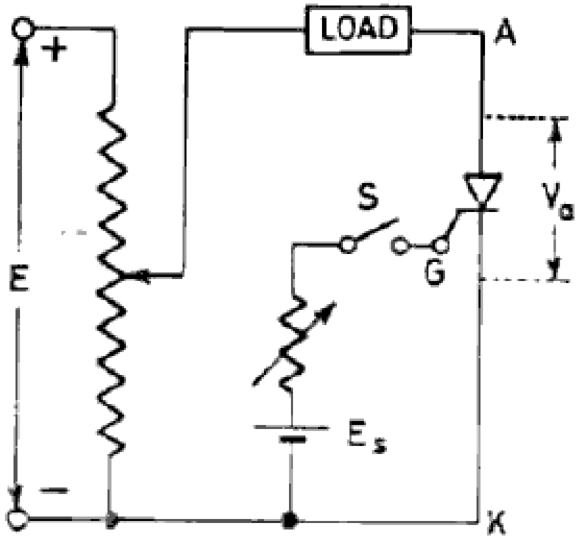


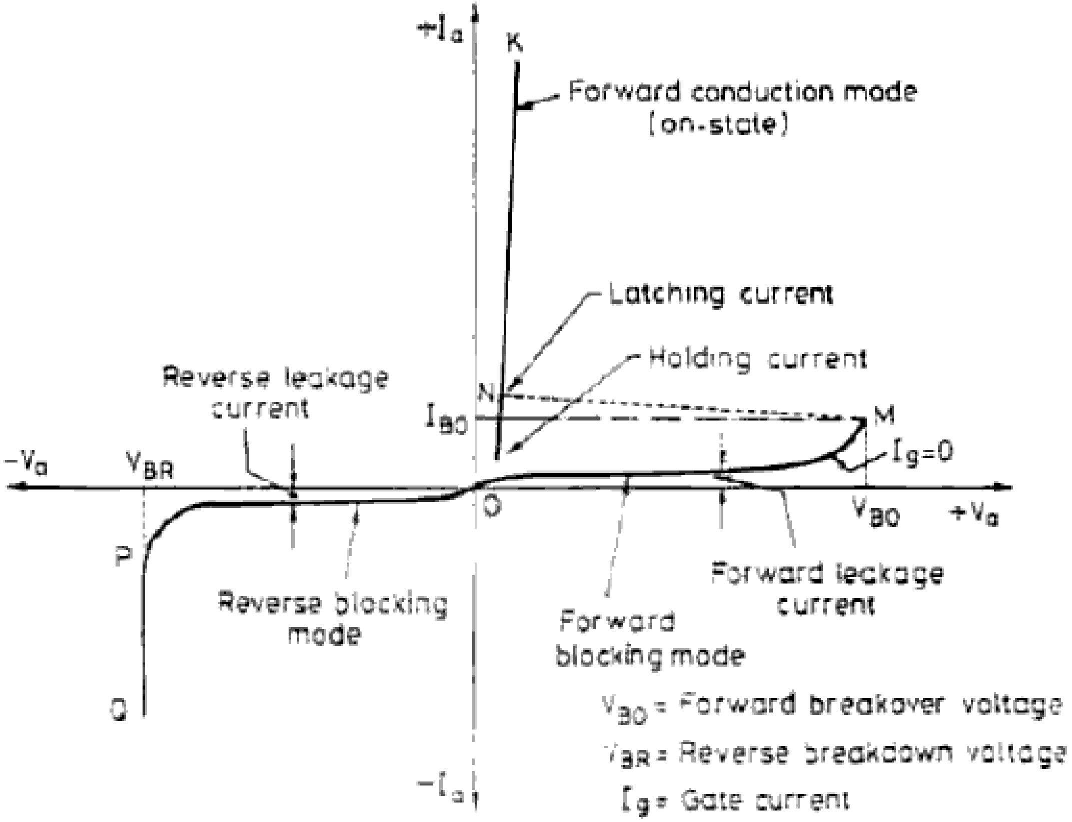
Average value of load voltage, $V_o = \dfrac{1}{\text{periodicity}} \displaystyle\int_{\alpha_1}^{\alpha_2} v_{ab} \,.\, d\,(\omega t)$

$$= \frac{3}{\pi}\int_{\pi/6}^{\pi/2} V_{ml} \sin(\omega t + 30°)\, d\,(\omega t) = \frac{3\,.\,V_{ml}}{\pi}$$

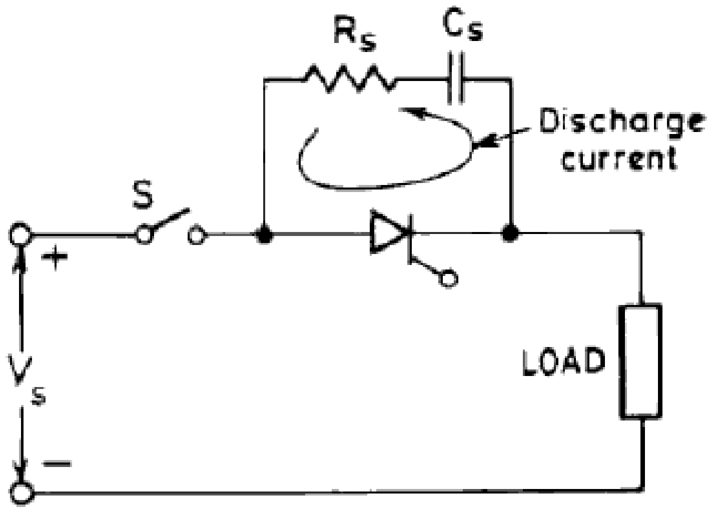
Thyristors


Threaded stud
Anode (Aluminium)
p
n
p
n
J1
J2
J3
Gate terminal welded to p region
Cathode
Anode
Gate
Cathode
A
G
K
A
G
K


LOAD
A
+
E
−
S
G
Va
Es
K


+Ia
K
Forward conduction mode (on-state)
Latching current
Holding current
Reverse leakage current
N
IBO
M
Ig=0
−Va
VBR
O
VBO
+Va
P
Q
Reverse blocking mode
Forward blocking mode
Forward leakage current
VBO = Forward breakover voltage
VBR = Reverse breakdown voltage
Ig = Gate current
−Ia

Design of Snubber Circuits:



Before SCR is fired by gate pulse, C_s charges to full voltage V_s. When the SCR is turned on, capacitor discharges through the SCR and sends a current equal to V_s/ (resistance of local path formed by C_s and SCR). As this resistance is quite low, the turn-on di/dt will tend to be excessive and as a result, SCR may be destroyed. In order to limit the magnitude of discharge current, a resistance R_s is inserted in series with C_s. Now when SCR is turned on, initial discharge current V_s/R_s is relatively small and turn-on di/dt is reduced.

$$V_s = (R_s + R_L)\, i + L\,\frac{di}{dt}$$

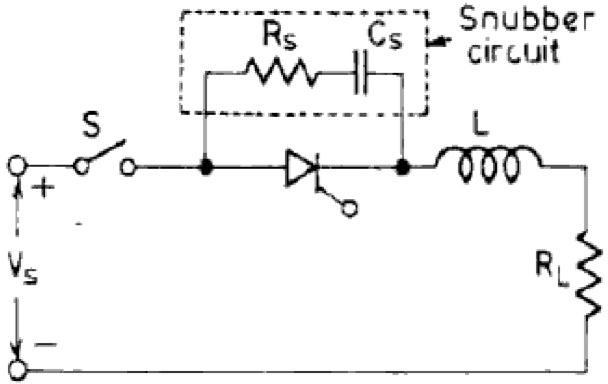
Its solution gives, $\quad i = I\,(1 - e^{-t/\tau})$

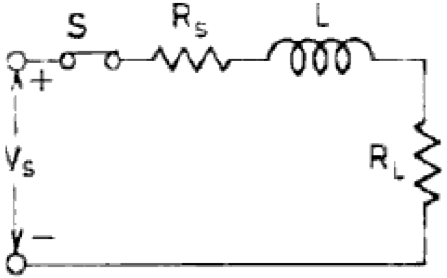
where $\quad I = \dfrac{V_s}{R_s + R_L} \quad$ and $\quad \tau = \dfrac{L}{R_s + R_L}$

$$\frac{di}{dt} = I \cdot e^{-t/\tau} \cdot \frac{1}{\tau} = \frac{V_s}{R_s + R_L} \cdot \frac{R_s + R_L}{L}\, e^{-t/\tau} = \frac{V_s}{L}\, e^{-t/\tau}$$

The value of di/dt is maximum when $t = 0$.

$$\left(\frac{di}{dt}\right)_{max} = \frac{V_s}{L} \quad \text{or} \quad L = \frac{V_s}{(di/dt)_{max}}$$





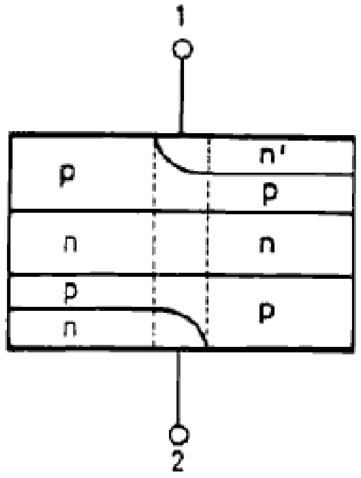
The voltage across SCR is given by, $v_a = R_s \cdot i$

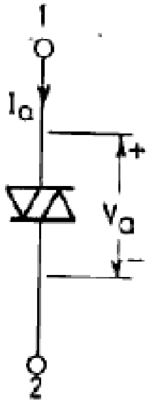
$$\frac{dv_a}{dt} = R_s \cdot \frac{di}{dt}$$

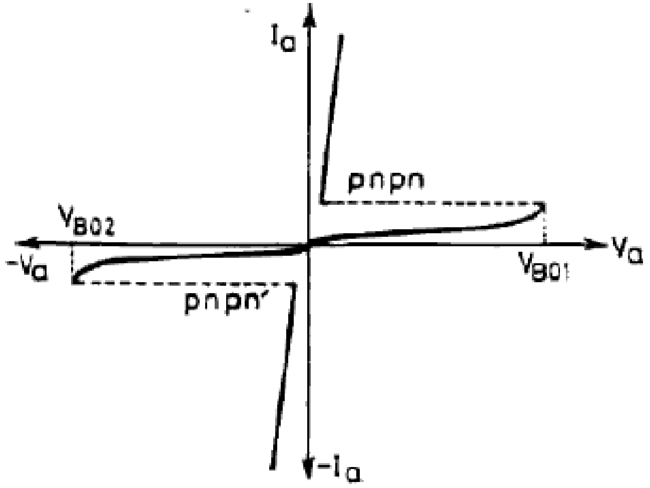
$$\left(\frac{dv_a}{dt}\right)_{max} = R_s \cdot \left(\frac{di}{dt}\right)_{max}$$

$$\left(\frac{dv_a}{dt}\right)_{max} = \frac{R_s \cdot V_s}{L} \quad \text{or} \quad R_s = \frac{L}{V_s}\left(\frac{dv_a}{dt}\right)_{max}$$

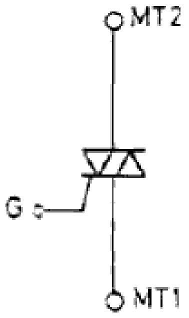
The Diac (Bidirectional Thyristor Diode)

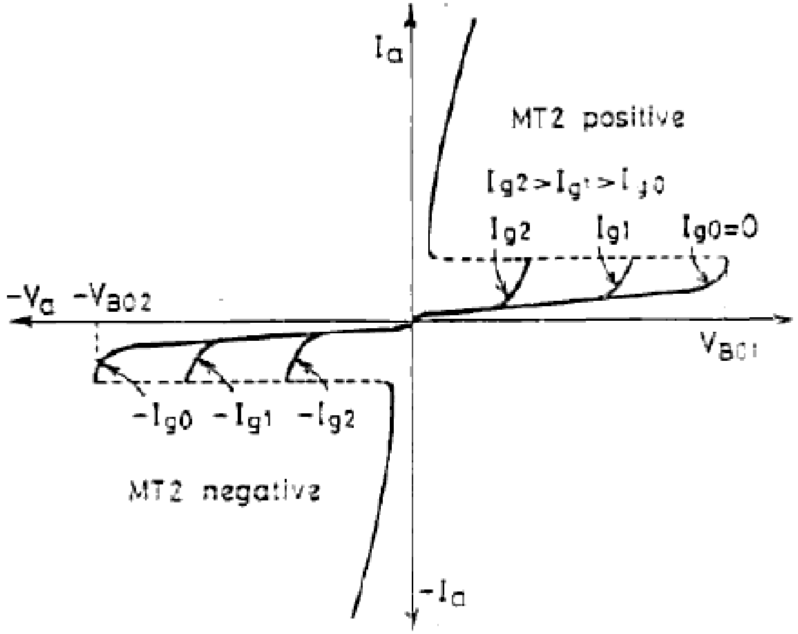




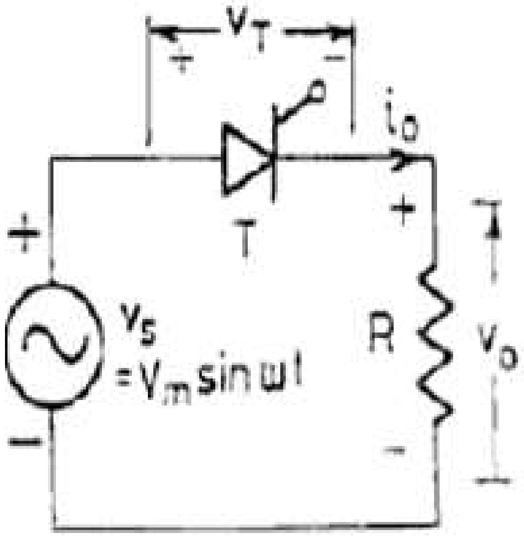


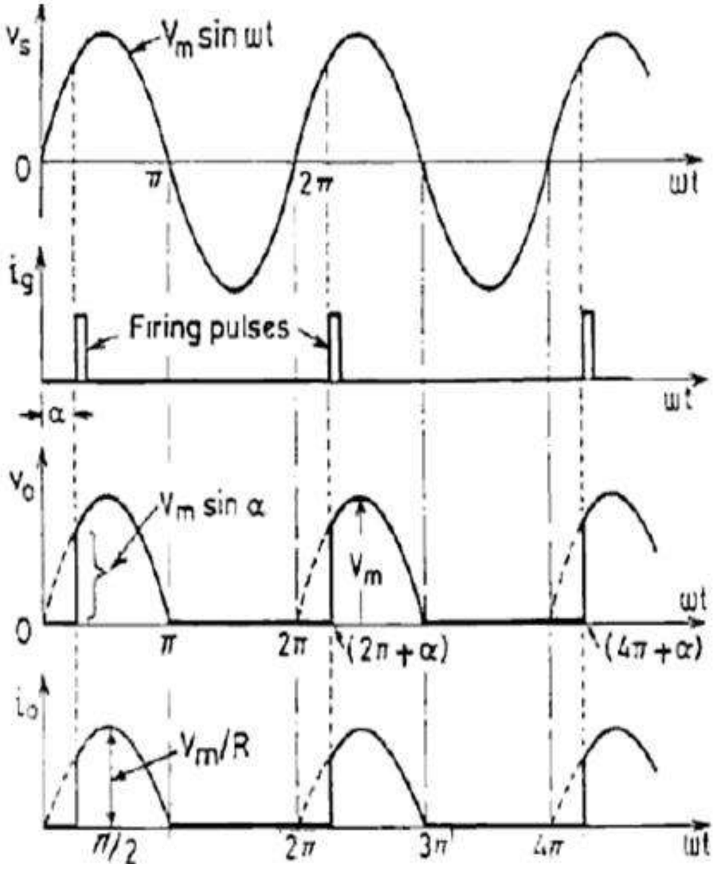
The Triac





Phase Controlled Rectifiers





Average voltage V_0 across load R in terms of firing angle α is given by

$$V_0 = \frac{1}{2\pi}\int_\alpha^\pi V_m \sin \omega t \cdot d(\omega t) = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

The maximum value of average output voltage V_0 occurs at $\alpha = 0°$.

$$\therefore \quad V_{o \cdot m} = \frac{V_m}{2\pi} \cdot 2 = \frac{V_m}{\pi}$$

Also,
$$V_0 = \frac{V_{om}}{2}(1 + \cos\alpha)$$

Average load current,
$$I_0 = \frac{V_0}{R} = \frac{V_m}{2\pi R}(1 + \cos\alpha)$$

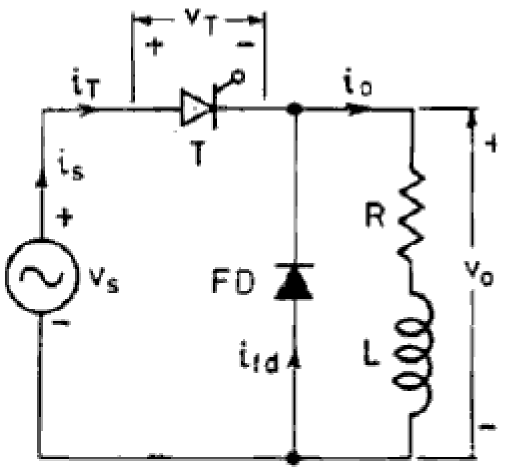
Rms voltage
$$V_{or} = \left[\frac{1}{2\pi}\int_\alpha^\pi V_m^2 \sin^2 \omega t \cdot d(\omega t)\right]^{1/2}$$

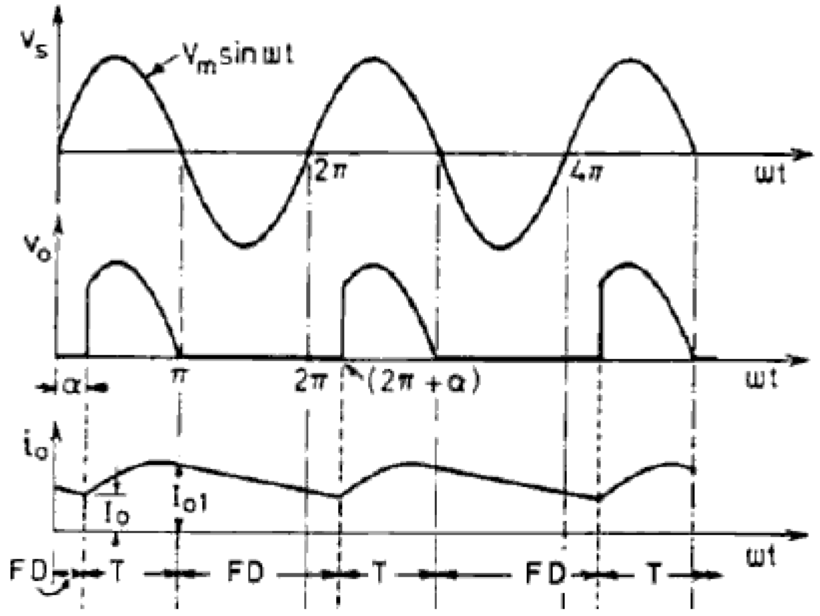
$$= \frac{V_m}{2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}\sin 2\alpha\right]^{1/2}$$

The value of rms current I_{or} is

$$I_{or} = \frac{V_{or}}{R}$$

Single-phase Half-wave Circuit with RL Load and Freewheeling Diode





Mode I : For conduction mode, the voltage equation is

$$V_m \sin \omega t = Ri_0 + L\frac{di_0}{dt}$$

Its solution, $$i_0 = \frac{V_m}{Z}\sin(\omega t - \phi) + A\, e^{-(R/L)t}$$

At $\omega t = \alpha$, $i_0 = I_0$, *i.e.* at $t = \frac{\alpha}{\omega}$, $i_0 = I_0$

$$\therefore \quad A = \left[I_0 - \frac{V_m}{Z}\sin(\alpha - \phi) \right\} e^{R\alpha/\omega L}$$

$$\therefore \quad i_0 = \frac{V_m}{Z}\sin(\omega t - \phi) + \left[I_0 - \frac{V_m}{Z}\sin(\alpha - \phi) \right\} \exp\left\{ -\frac{R}{L}\left(t - \frac{\alpha}{\omega} \right) \right\}$$

Note that for mode I, $\alpha \le \omega t \le \pi$

$$0 = Ri_0 + L\,\frac{d\,i_0}{dt}$$

Its solution is $\qquad i_0 = A\,e^{-(R/L)t}$

At $\omega t = \pi$, $\qquad i_0 = I_{01}$.

It gives $\qquad A = I_{01}\,e^{R\pi/\omega L}$

$\therefore \qquad i_0 = I_{01} \cdot \exp\left[-\frac{R}{L}\left(t - \frac{\pi}{\omega}\right)\right]$

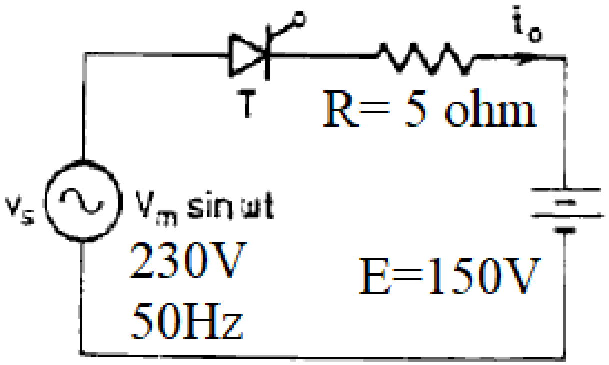
Note that for mode II, $\pi < \omega t \le (2\pi + \alpha)$

Average load voltage V_0 from Fig. 6.3 (*b*) is given by

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin \omega t\; d\,(\omega t) = \frac{V_m}{2\pi}\,(1 + \cos \alpha)$$

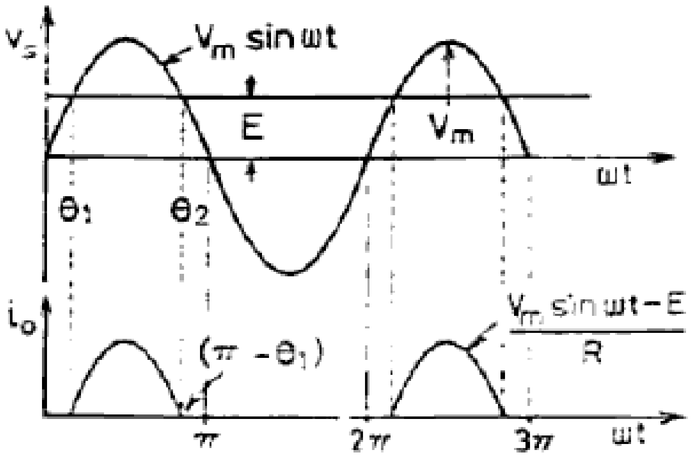
Average load current, $I_0 = \frac{V_0}{R} = \frac{V_m}{2\pi R}\,(1 + \cos \alpha)$

Example



$$V_m \sin \omega t = E + i_0 R \qquad \text{or} \qquad i_0 = \frac{V_m \sin \omega t - E}{R}$$

It is seen that SCR is turned on when $V_m \sin \theta_1 = E$ and is turned off when $V_m \sin \theta_2 = E$, where $\theta_2 = \pi - \theta_1$. The battery charging requires only the average current I_0 given by



$$I_0 = \frac{1}{2\pi R}\left[\int_{\theta_1}^{\pi - \theta_1} (V_m \sin \omega t - E)\, d(\omega t)\right]$$

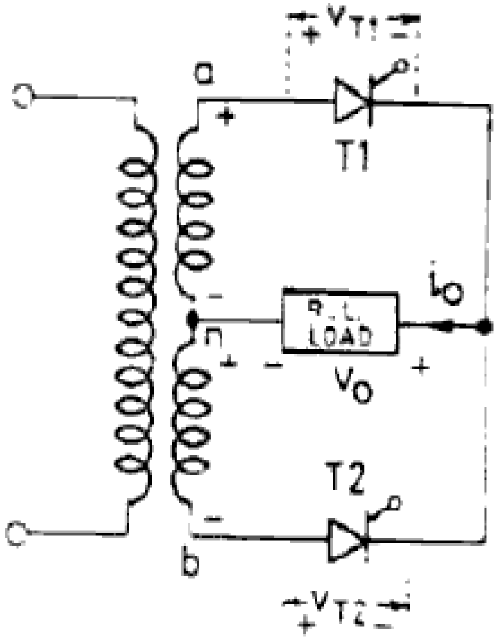
$$= \frac{1}{2\pi R}\,[2V_m \cos \theta_1 - E(\pi - 2\theta_1)]$$

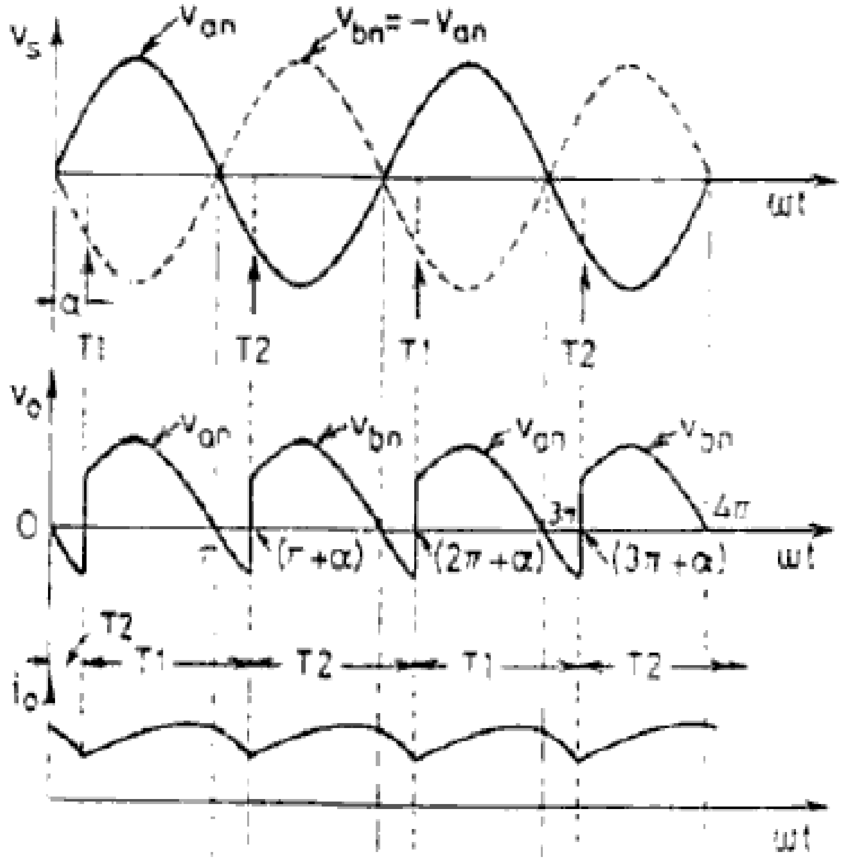
Here $\theta_1 = \sin^{-1} \dfrac{150}{\sqrt{2} \cdot 230} = 27.466°$

$$\therefore \quad I_0 = \frac{1}{2\pi \cdot 8}\left[2 \cdot \sqrt{2} \cdot 230 \cos 27.466° - 150\left(\pi - \frac{2 \times 27.496 \times \pi}{180}\right)\right] = 4.9676 \text{ A.}$$

Power supplied to battery $= EI_0 = 150 \times 4.9676 = 745.14$ W.

Single-phase full-wave converter





turn off time to thyristor $t_c = \dfrac{\pi-\alpha}{\omega}$

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} V_m \sin\omega t \cdot d(\omega t) = \frac{2V_m}{\pi}\cos\alpha$$

Three-phase Half-wave Controlled Converter

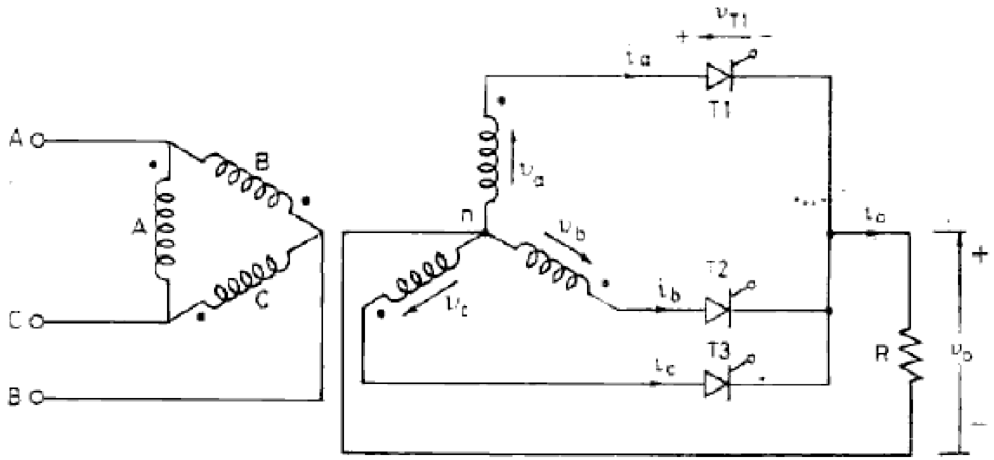
Average value of output voltage, $V_o = \frac{3}{2\pi} \int_{\alpha+\frac{\pi}{6}}^{\alpha+\frac{5\pi}{6}} V_{mp} \sin \omega t \, d(\omega t)$

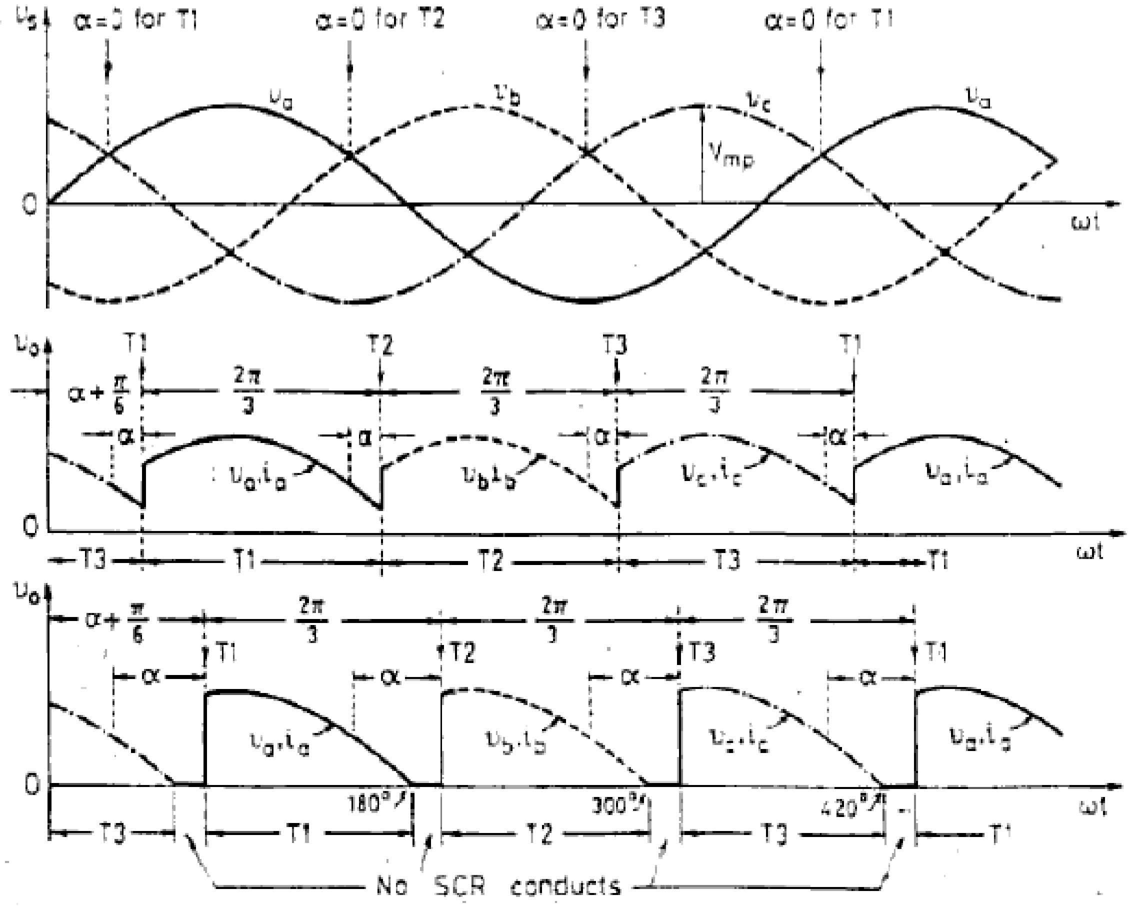
$$= \frac{3\sqrt{3}}{2\pi} V_{mp} \cdot \cos\alpha = \frac{3 V_{ml}}{2\pi} \cos\alpha$$

V_{mp} = maximum value of phase (line to neutral) voltage

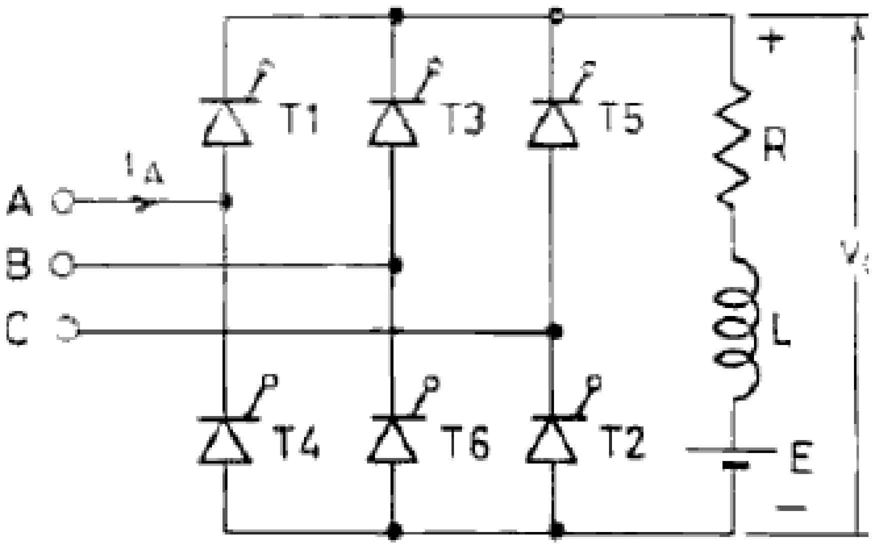
V_{ml} = maximum value of line voltage = $\sqrt{3} \cdot V_{mp}$

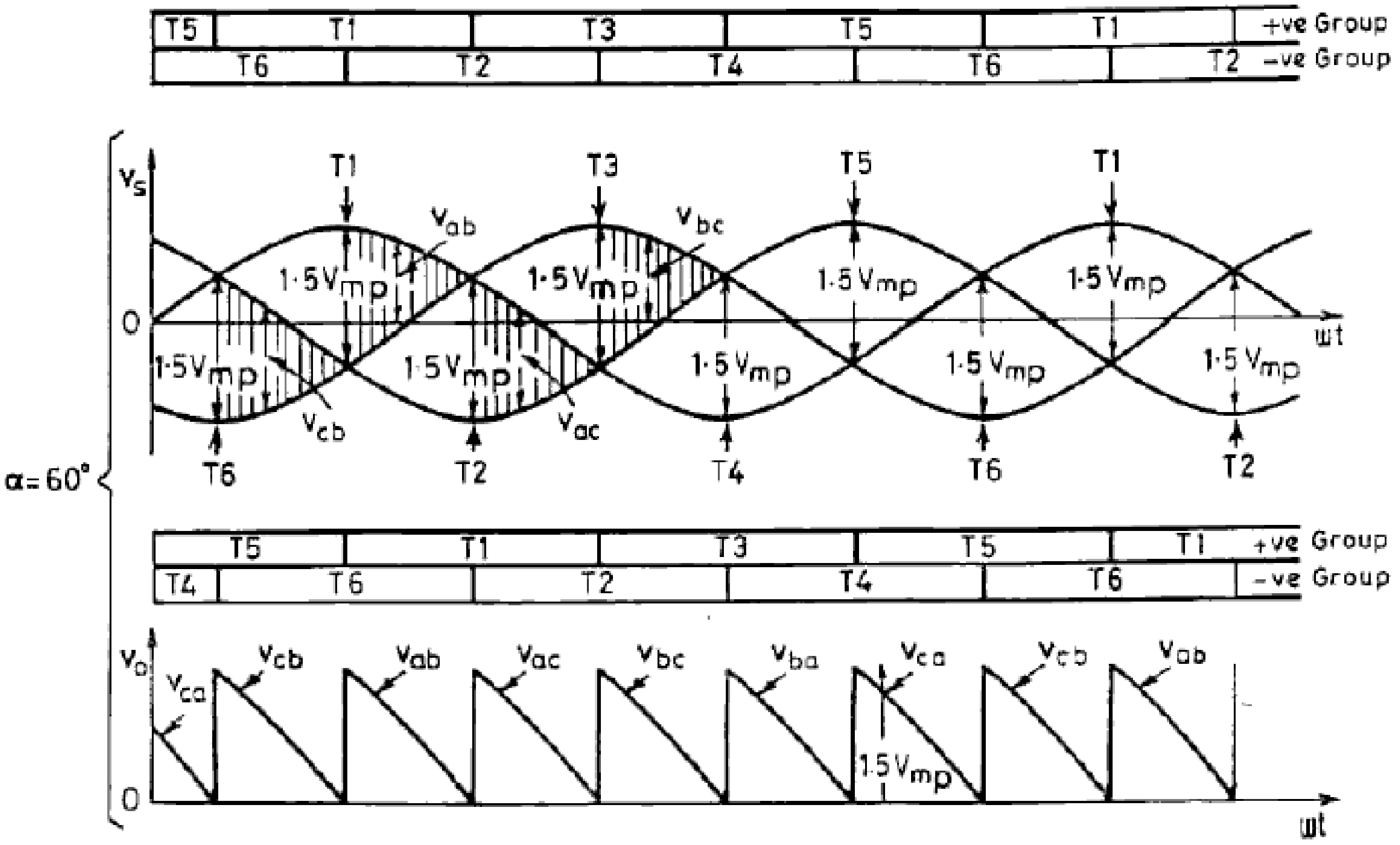
α = firing-angle delay





Three-phase Full Converters

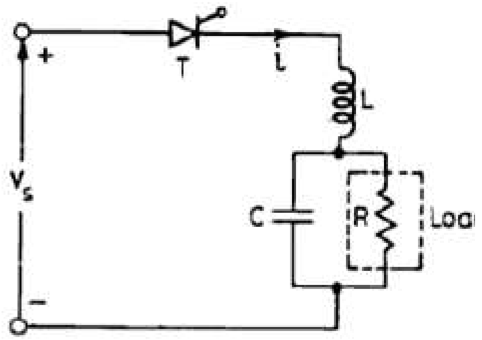


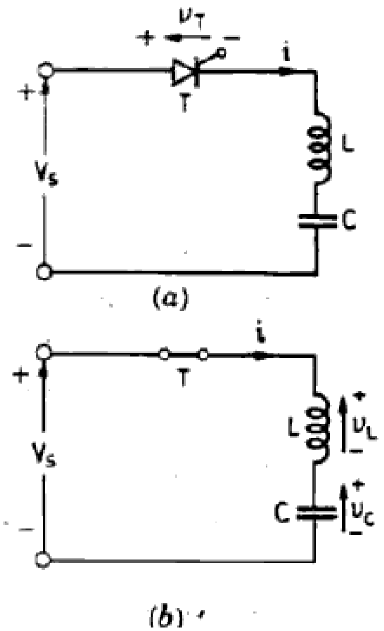


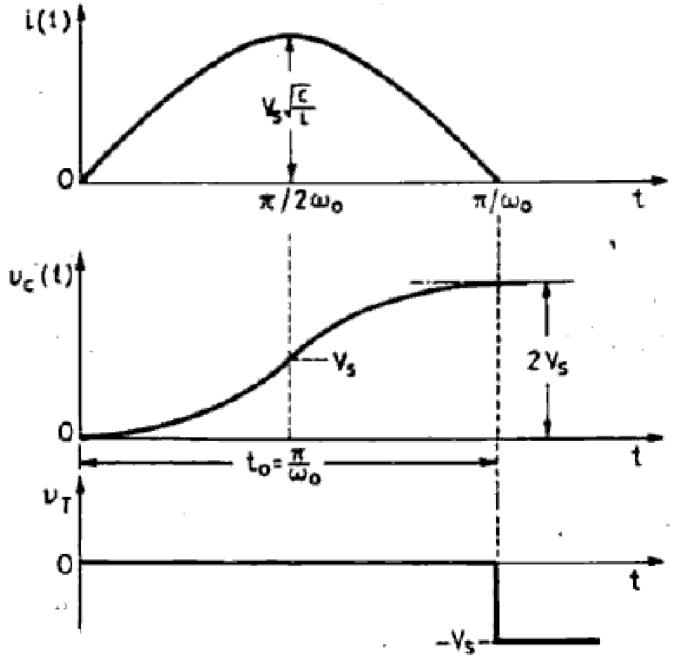
Thyristor Commutation Techniques

Commutation is defined as the process of turning-off a thyristor. For the purpose of power control or power conditioning, a conducting thyristor must be turned-off as desired.

Load Commutation







$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = V_s$$

Its solution, $i(t) = V_s\sqrt{\frac{C}{L}}\sin\omega_0 t$

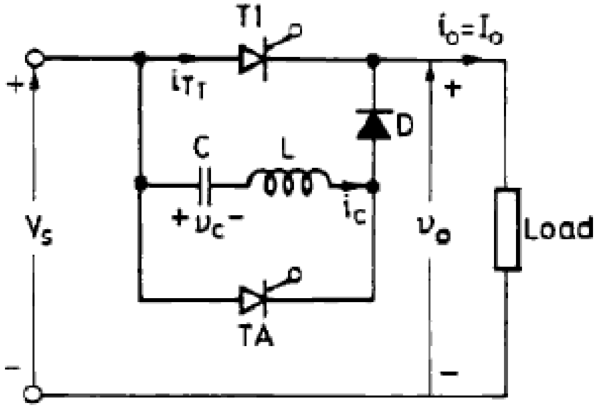
Here $\omega_0 = \frac{1}{\sqrt{LC}}$ is called the resonant frequency of the circuit.

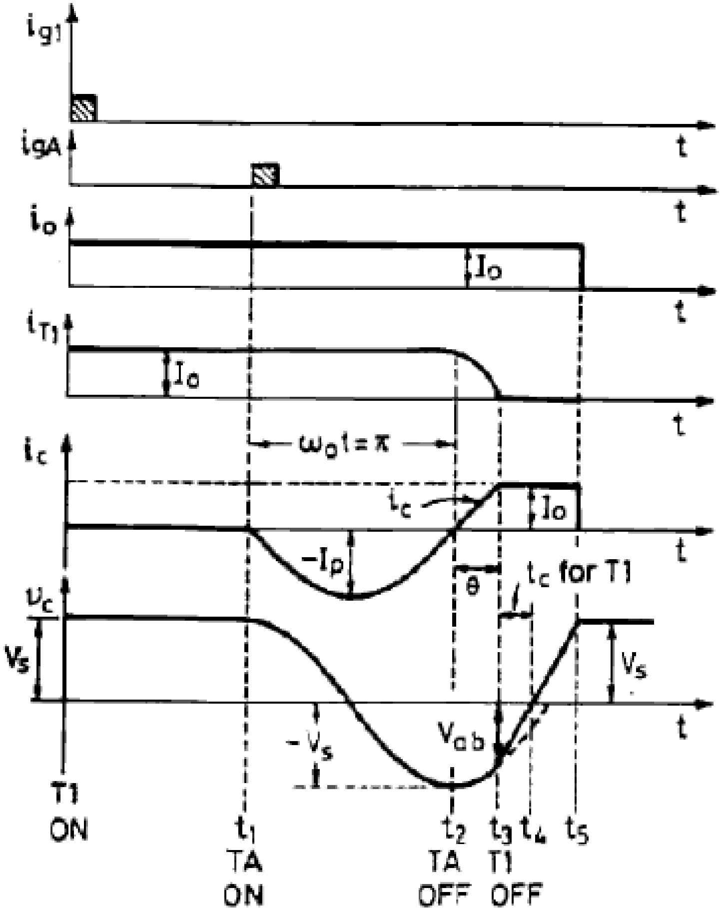
Capacitor voltage is $v_c(t) = V_s(1 - \cos\omega_0 t)$

It is seen from above equations that at time $t = t_0 = \pi/\omega_0$, $i(t) = 0$ and $v_c(t) = +2V_s$.

t_0 = conduction time of the thyristor $= \pi\sqrt{LC}$

Resonant-pulse commutation





When T1 is turned on at $t = 0$, a constant current I_0 is established in the load circuit. Here, for simplicity, load current is assumed constant.

TA is gated at $t = t_1$. a resonant current i_c begins to flow from *C* through *TA*, *L* and back to *C*.

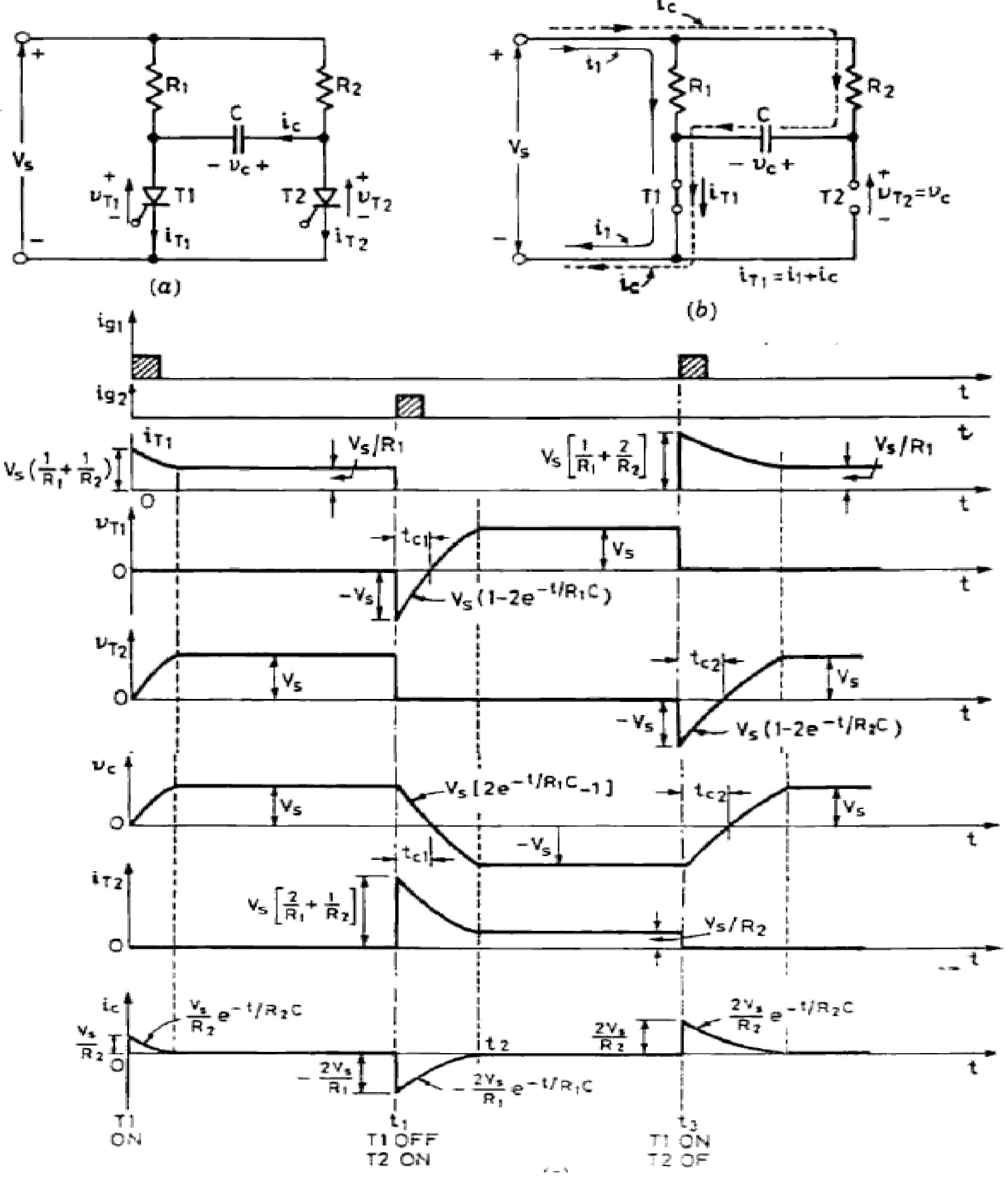
$$i_c = -V_s\sqrt{\frac{C}{L}}\sin\omega_0 t = -I_p\sin\omega_0 t$$

$$v_c(t) = \frac{1}{C}\int i_c\,dt = V_s\cos\omega_0 t$$

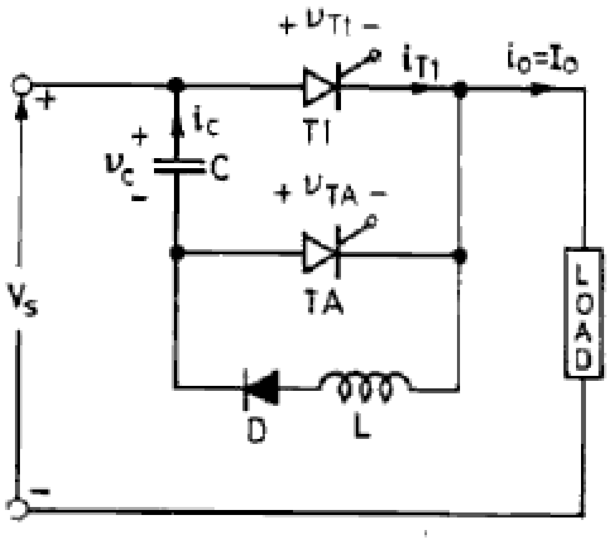
After π radians from instant t_1, *i.e.* just after instant t_2, as i_c tends to reverse, *TA* is turned off at t_2. With $v_c = -V_s$, Resonant current i_c now builds up through *C*, *L*, *D* and T1. As this current i_c grows opposite to forward thyristor current of T1, current $i_{T1} = I_0 - i_c$ begins to decrease.

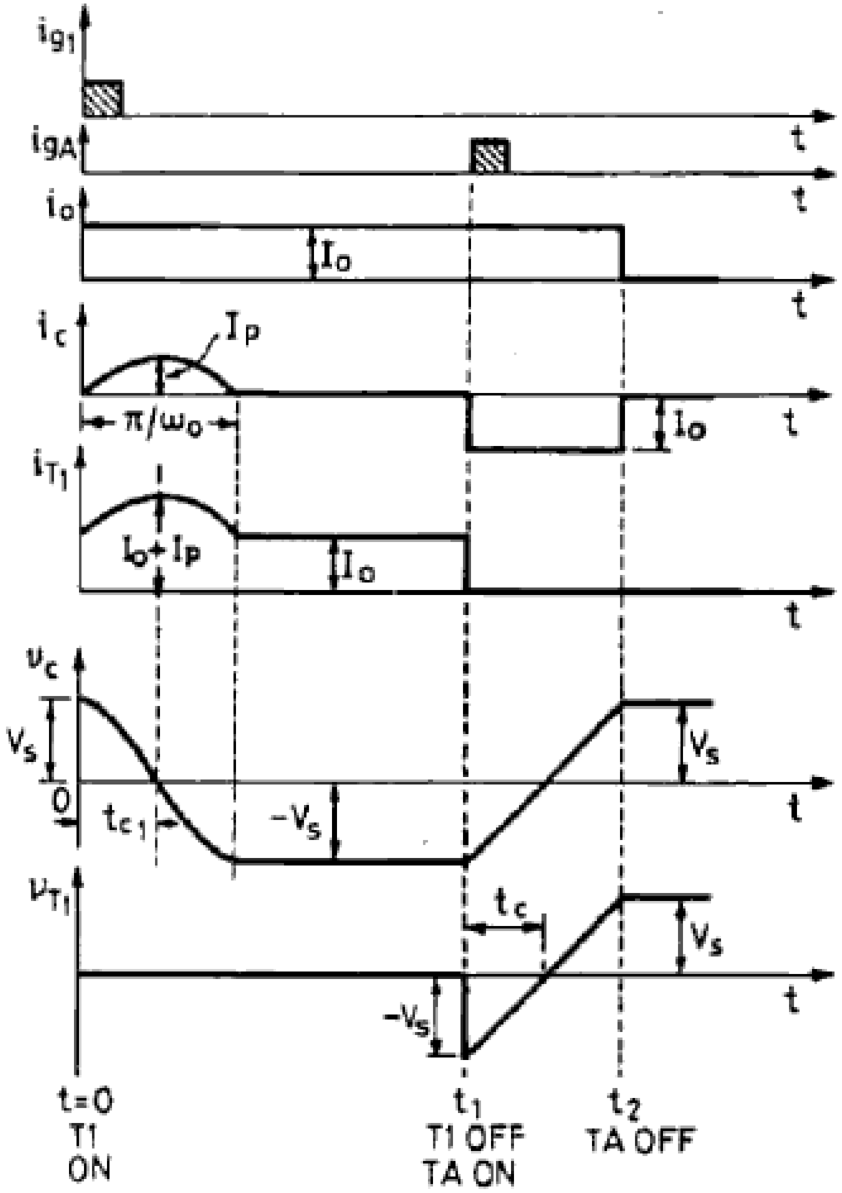
Finally, when i_c in the reversed direction attains the value I_0, forward current in T1 ($i_{T1} = I_0 - I_0 = 0$) is reduced to zero and the device T1 is turned off at t_3.

Complementary Commutation



Impulse Commutation

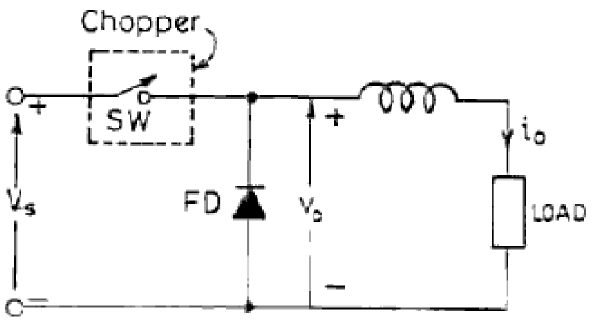


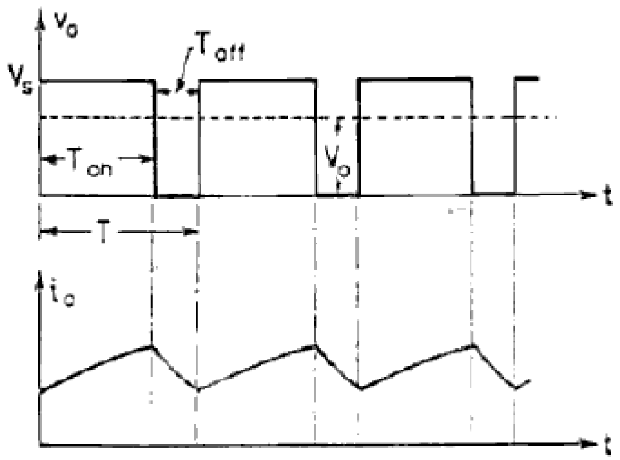


Choppers

A chopper is a static device that converts fixed dc input voltage to a variable dc output voltage directly. Choppers are now being used all over the world for rapid transit systems. These are also used in trolley cars, marine hoists, forklift trucks and mine haulers . The future electric automobiles are likely to use choppers for their speed control and braking. Chopper systems offer smooth control, high efficiency, fast response and regeneration.

step-down chopper (Buck)





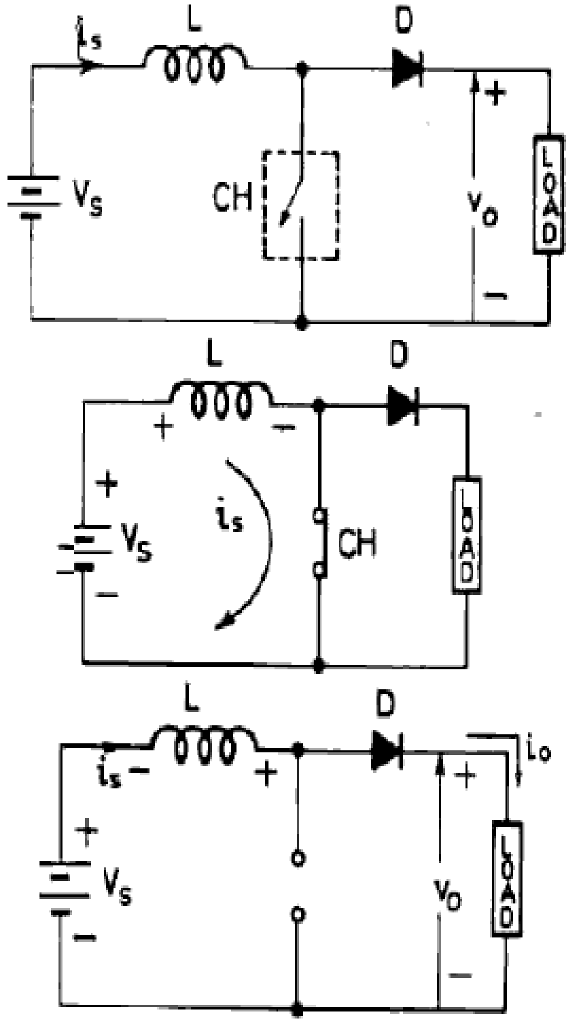
average load voltage V_0 is given by

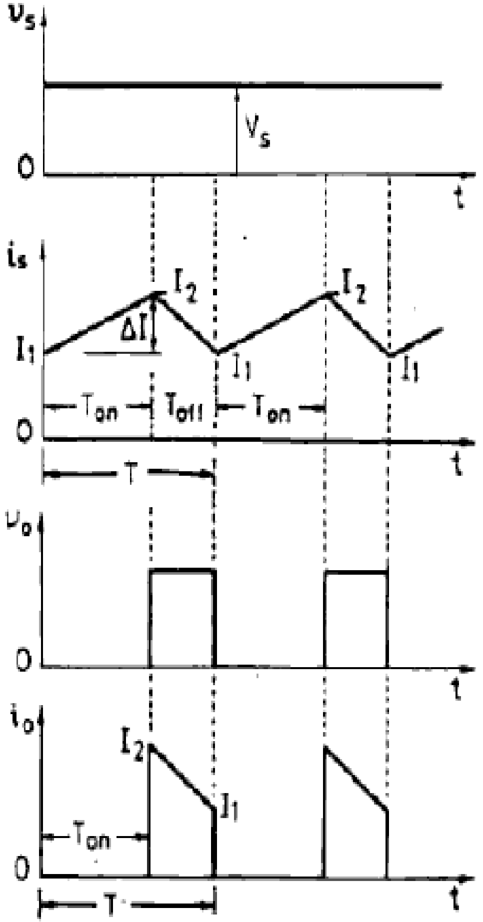
$$V_0 = \frac{T_{on}}{T_{on} + T_{off}} V_s = \frac{T_{on}}{T} V = \alpha V_s$$

T_{on} = on–time ; T_{off} = off–time $\quad T = T_{on} + T_{off}$ = chopping period

$\alpha = \frac{T_{on}}{T}$ = duty cycle $\qquad V_0 = f \cdot T_{on} \cdot V_s \qquad f = \frac{1}{T}$ = chopping frequency

step-up chopper (Boost)





Assuming linear variation of output current, the energy input to inductor from the source, during the period T_{on}, is

$$W_{in} = \text{(voltage across } L\text{) (average current through } L\text{) } T_{on}$$

$$= V_s \cdot \left(\frac{I_1 + I_2}{2}\right) T_{on}$$

During the time T_{off}, when chopper is off, the energy released by inductor to the load is

$$W_{off} = \text{(voltage across } L\text{) (average current through } L\text{) } T_{off}$$

$$= (V_0 - V_s)\left(\frac{I_1 + I_2}{2}\right) \cdot T_{off}$$

$$V_s \left(\frac{I_1 + I_2}{2}\right) T_{on} = (V_0 - V_s)\left(\frac{I_1 + I_2}{2}\right) \cdot T_{off}$$

$$V_s \cdot T_{on} = V_o T_{off} - V_s \cdot T_{off}$$

$$V_o T_{off} = V_s (T_{on} + T_{off}) = V_s \cdot T$$

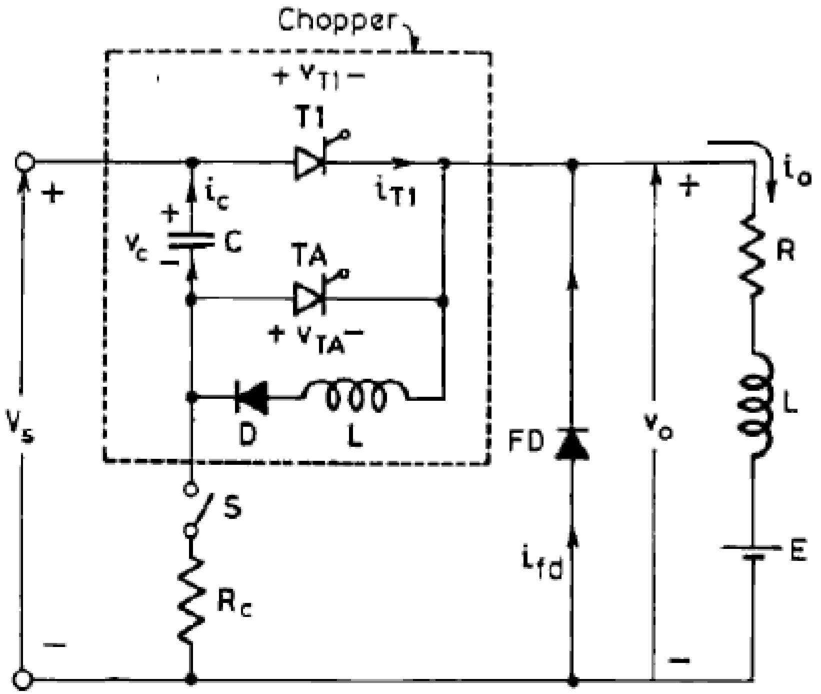
$$V_o = V_s \frac{T}{T_{off}} = V_s \frac{T}{T - T_{on}} = V_s \frac{1}{1 - \alpha}$$

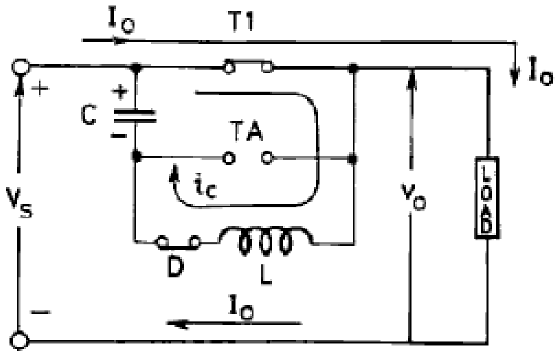
Voltage Commutated Chopper

Working of this chopper can start only if the capacitor C is charged with polarities as marked in Fig. This can be achieved in one of the two ways as under:

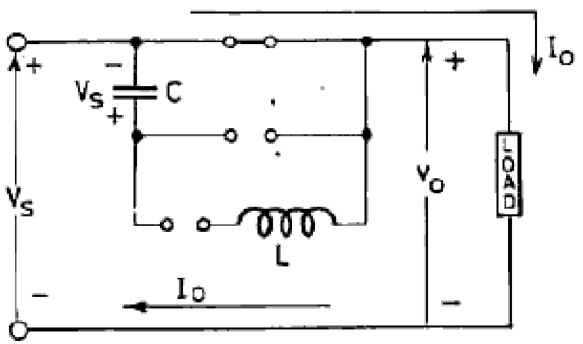
(1) Close switch S so that capacitor gets Vs charged to voltage V, through source *Vs*, C, *S* and charging resistor *Rc*. Switch *S* is then opened.

(2) Auxiliary thyristor TA is triggered so that C gets charged through source Vs, C, TA and the load. The charging current through capacitor C decays and as it reaches zero, $V_c = V_s$ and TA is turned off.

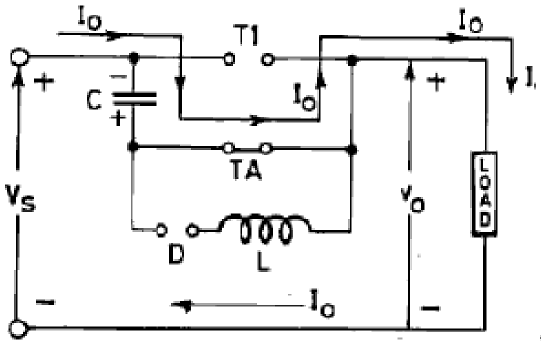




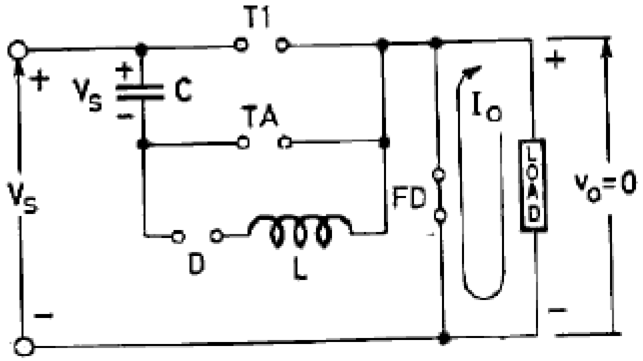
(a) Mode I, $0 < t < t_1$



(b) Mode II, $t_1 \le t \le t_2$



(c) Mode III, $t_2 \le t < t_3$



(d) Mode IV, $t_3 \le t < T$

Inverters

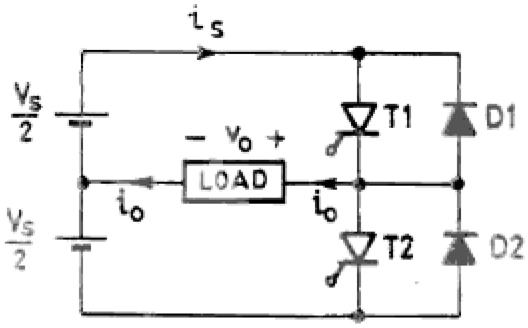
A device that converts de power into ac power at desired output voltage and frequency is called an inverter. Some industrial applications of inverters are for adjustable-speed ac drives, induction heating, stand by air-craft power supplies, UPS (uninterruptible power supplies) for computers, HVDC transmission lines etc.

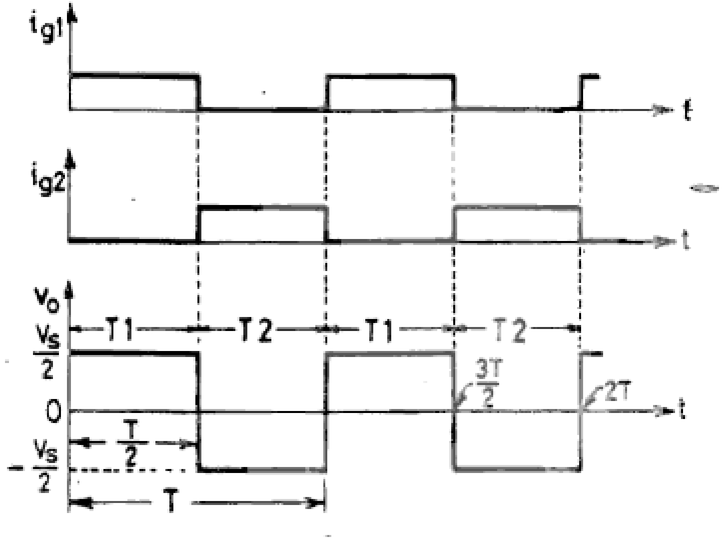
Single-phase Bridge Inverters

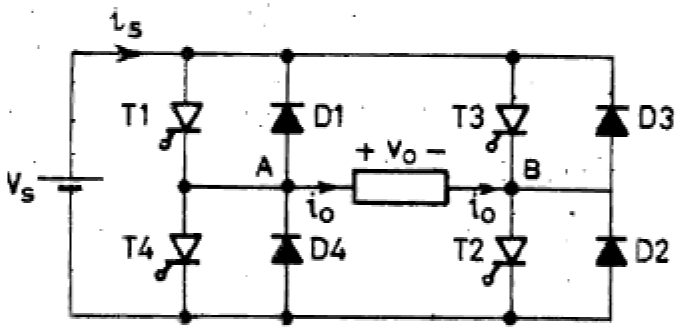
Single-phase bridge inverters are of two types, namely:

(i) single-phase half-bridge inverters and

(ii) single-phase full-bridge inverters.







is
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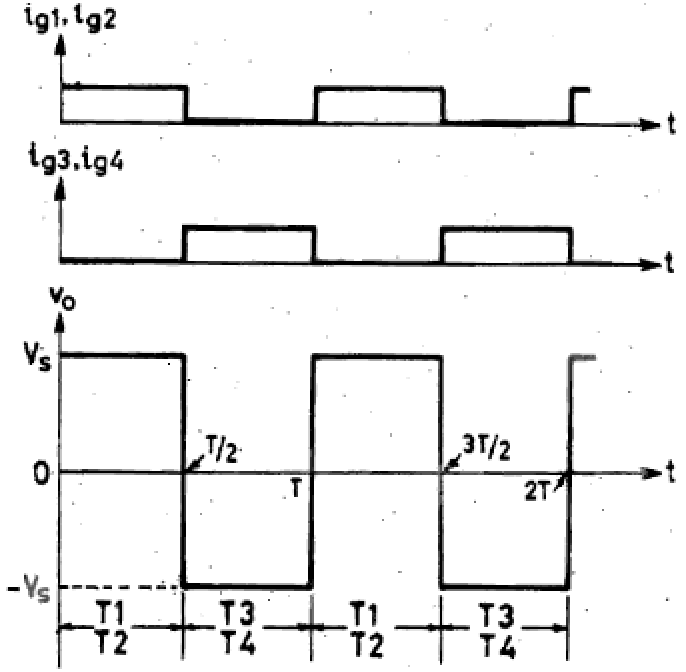

ig1, ig2
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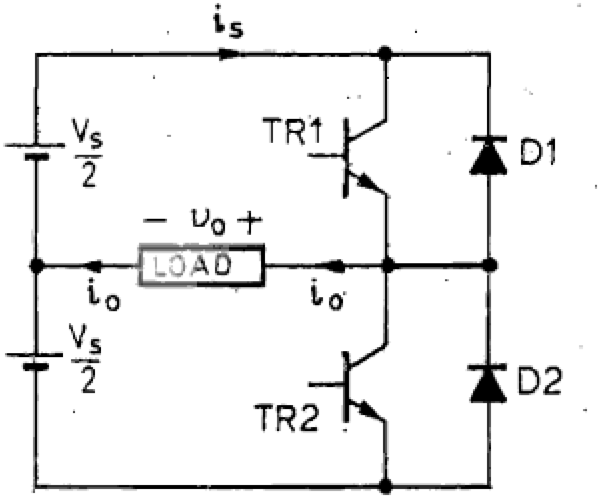

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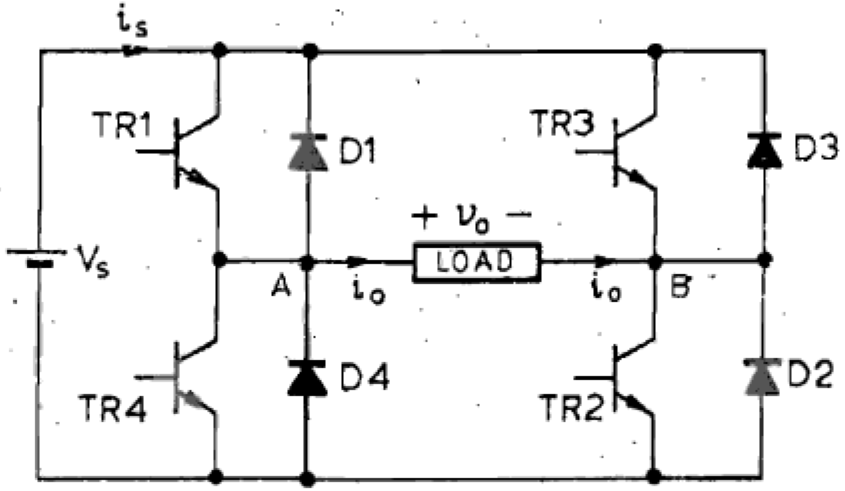

is
Vs
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io
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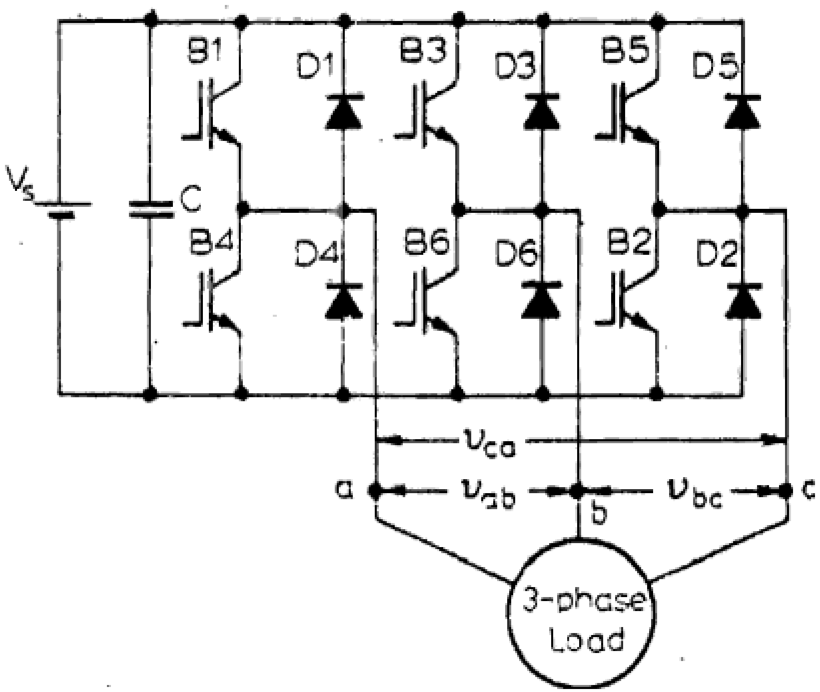
D2

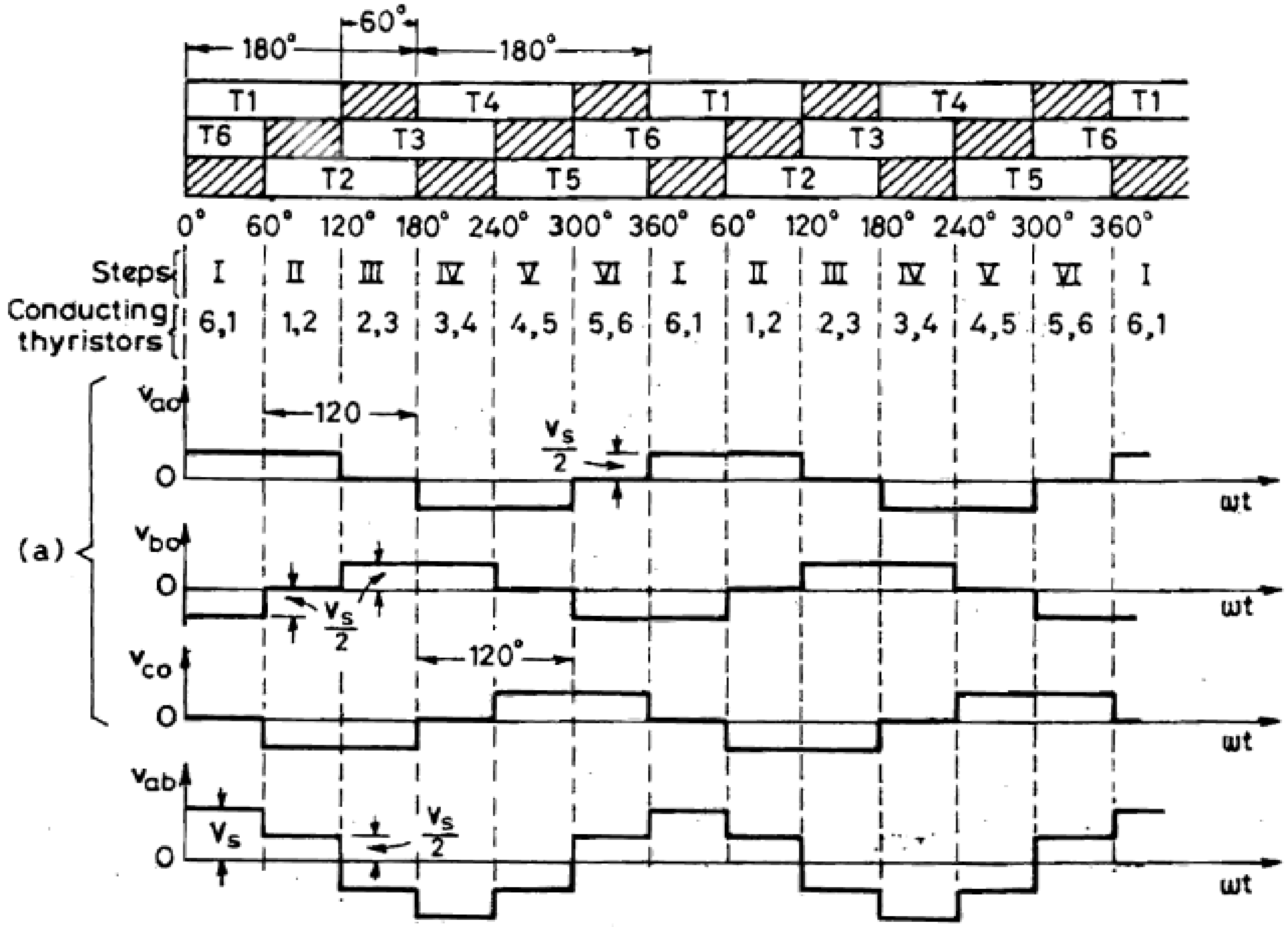
Three Phase Inverters:

For providing adjustable-frequency power to industrial applications, three-phase inverters are more common than single-phase inverters. Three-phase inverters, like single-phase inverters, take their dc supply from a battery or more usually from a rectifier. A basic three-phase inverter is a six-step bridge inverter. It uses a minimum of six thyristors. In inverter terminology, a step is defined as a change in the firing from one thyristor to the next thyristor in proper sequence. For one cycle of 360°, each step would be of 60° interval for a six-step inverter. This means that thyristors would be gated at regular intervals of 60° in proper sequence so that a 3-phase ae voltage is synthesized at the output terminals of a six-step inverter.



Three-phase 120 Degree Mode VSI

For the 120-degree mode VSI, each thyristor conducts for 120° of a cycle.



Multiple-Pulse Modulation

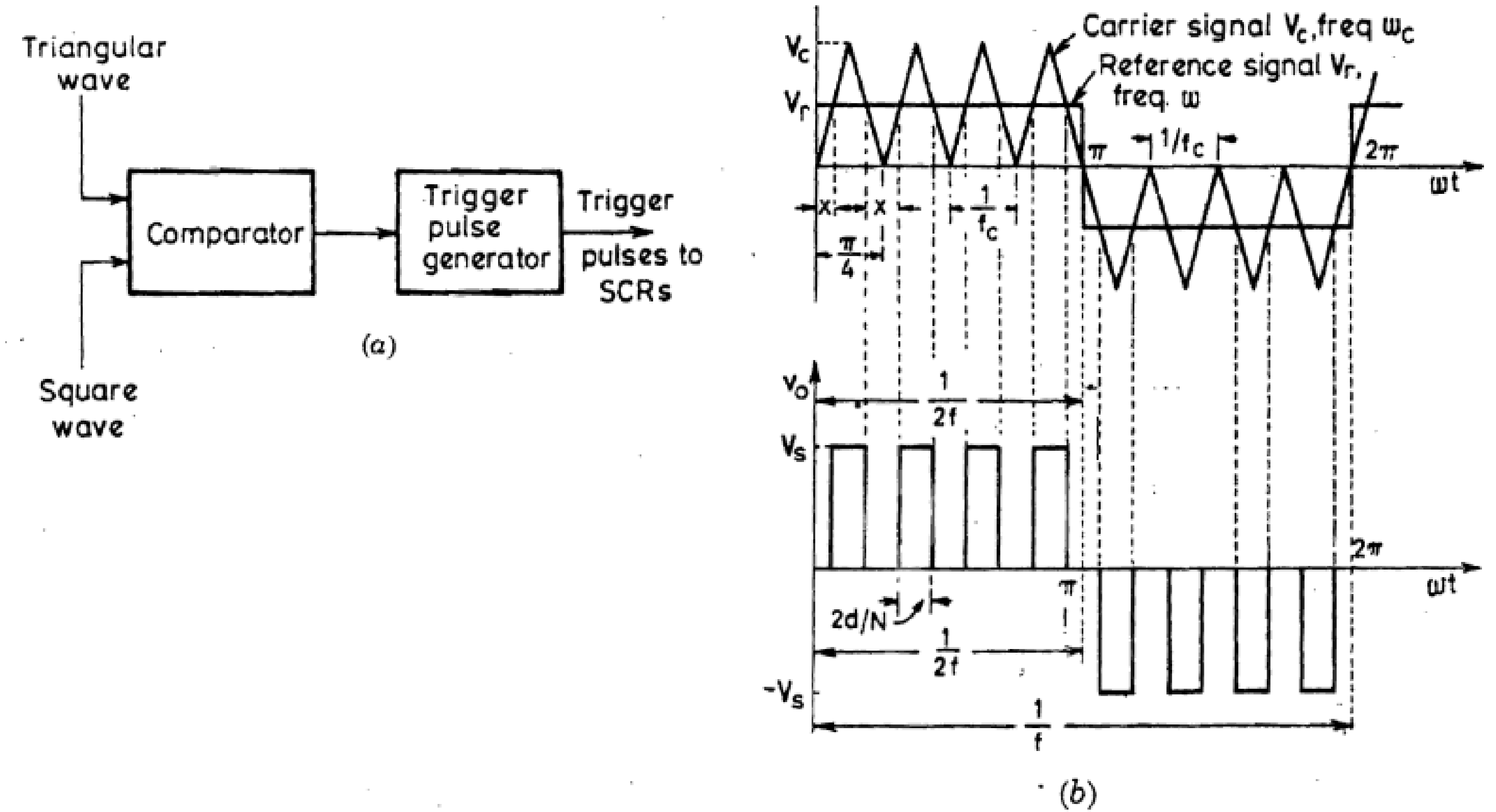
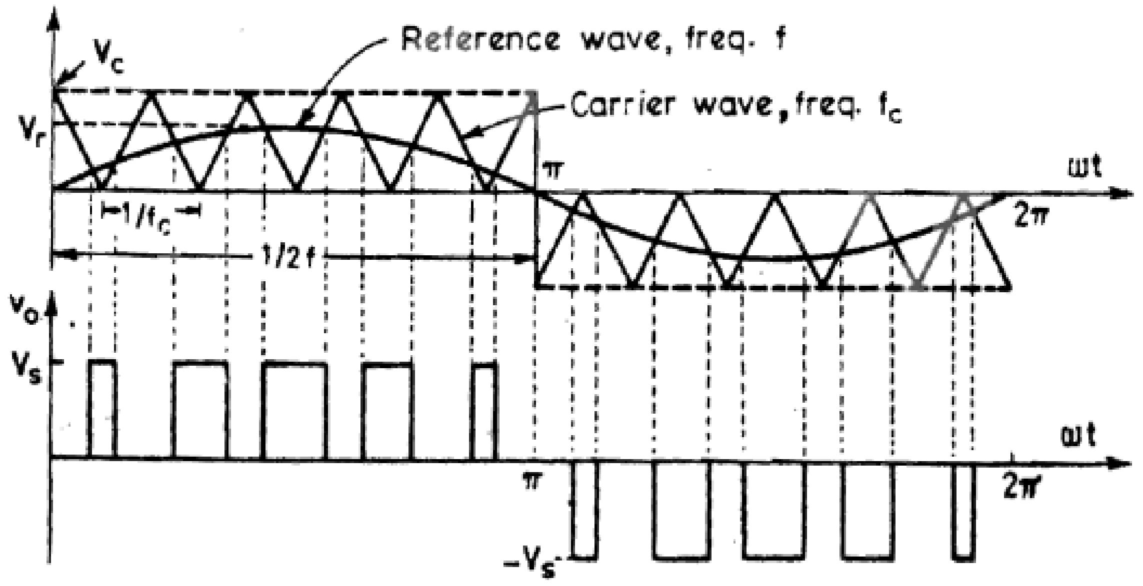


Fig. (a) Pertaining to multiple-pulse modulation (MPM) (b) Output voltage waveform

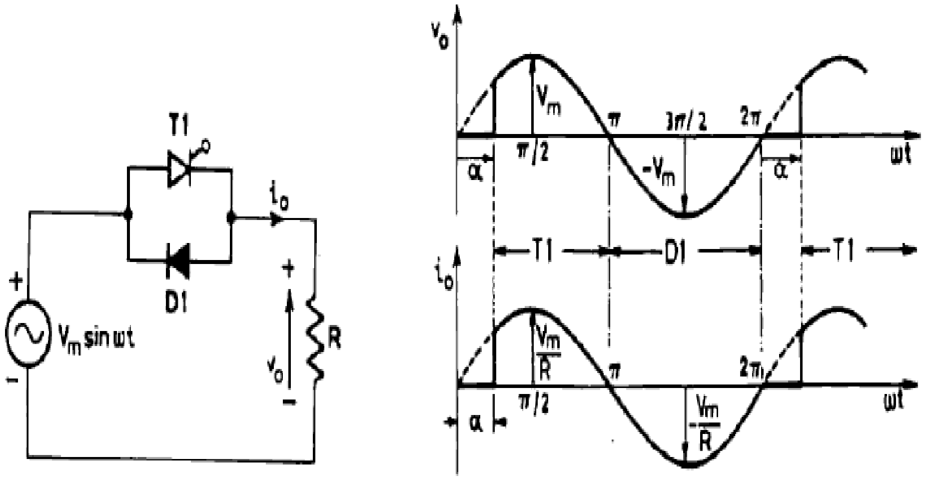
Sinusoidal-Pulse Modulation (SPWM)

In this method of modulation, several pulses per half cycle reused as in the case of multiple-pulse modulation (MPM). In MPM, the pulse width is equal for all the pulses. But in SPWM, the pulse width is a sinusoidal function of the angular position of the pulse in a cycle. For realizing SPWM, a high frequency triangular carrier wave V_c is compared with a sinusoidal reference wave V_r of the desired frequency. The intersection of V_c and V_r waves determines the switching instants.



AC Voltage Controllers

AC voltage controllers are thyristor based devices which convert fixed alternating voltage directly to variable alternating voltage without a change in the frequency. Some of the main applications of ae voltage controllers are for domestic and industrial heating, transformer tap changing, lighting control, speed control of single phase and three phase ac drives and starting of induction motors.

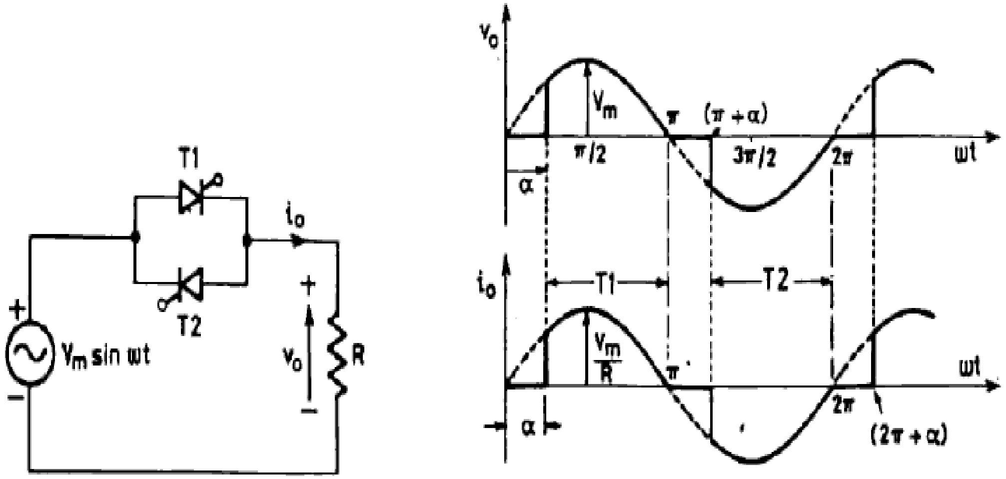


Average value of output voltage is, $V_o = \frac{1}{2\pi} \int_{\alpha}^{2\pi} V_m \sin \omega t \, . \, d\,(\omega t)$

or

$$V_o = \frac{V_m}{2\pi} \mid -\cos \omega t \mid_{\alpha}^{2\pi}$$

$$= \frac{V_m}{2\pi} (\cos \alpha - 1)$$



(a) (b)

Fig. Single-phase full-wave ac voltage controller (a) Power-circuit diagram and (b) voltage and current waveforms.

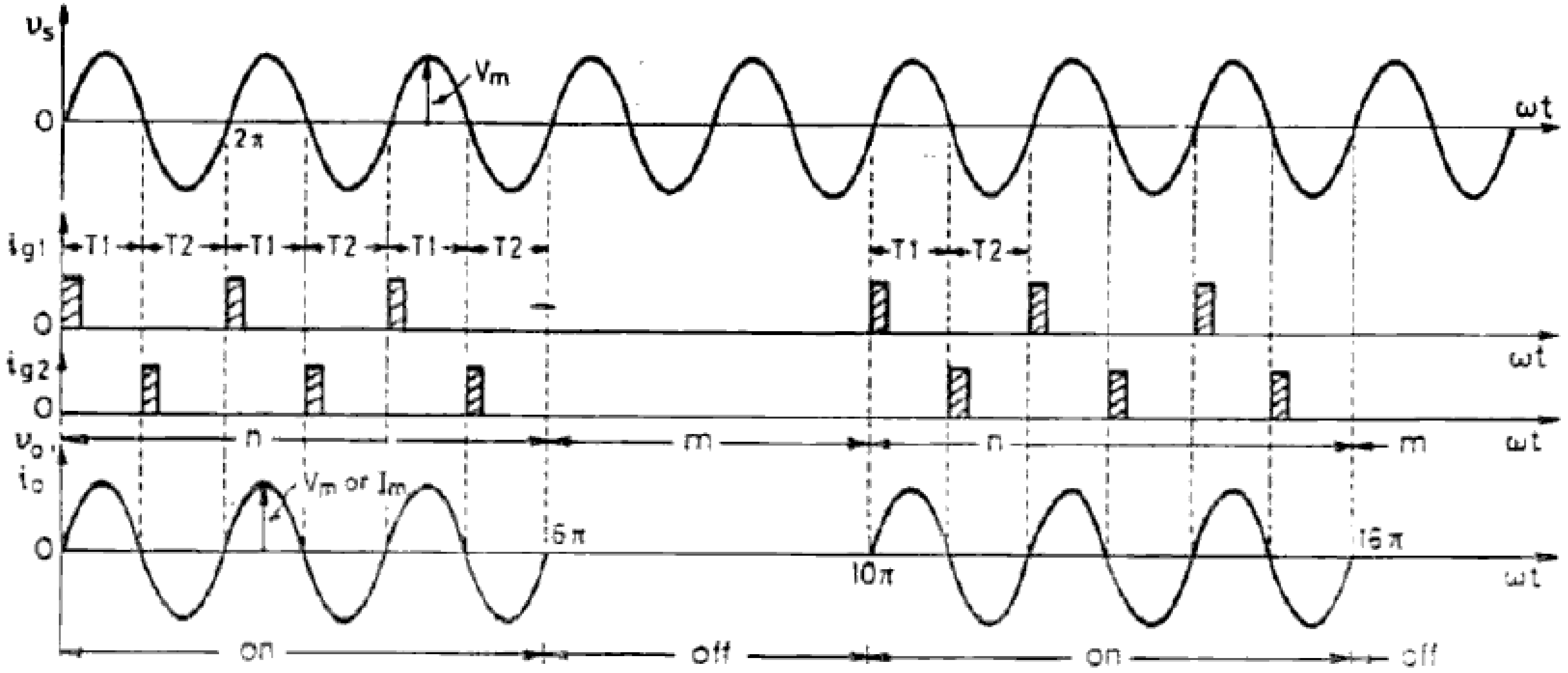
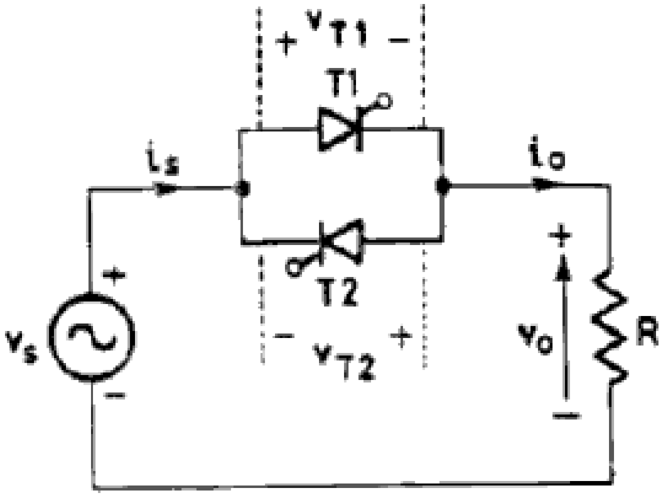
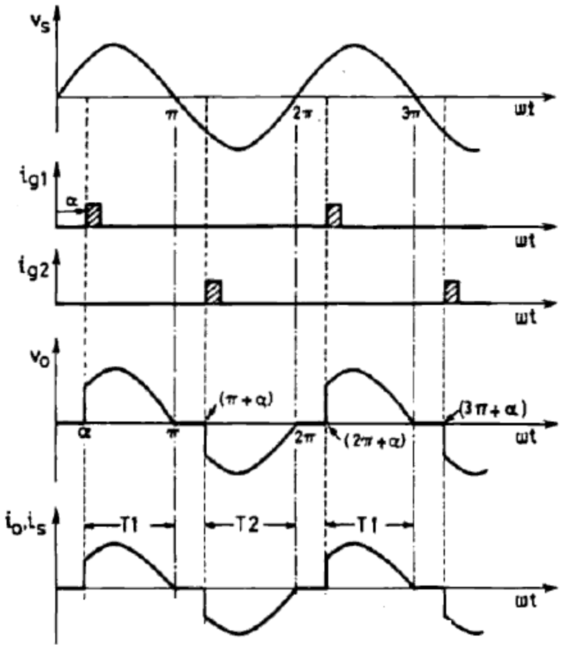


Fig. . Waveforms pertaining to integral cycle control

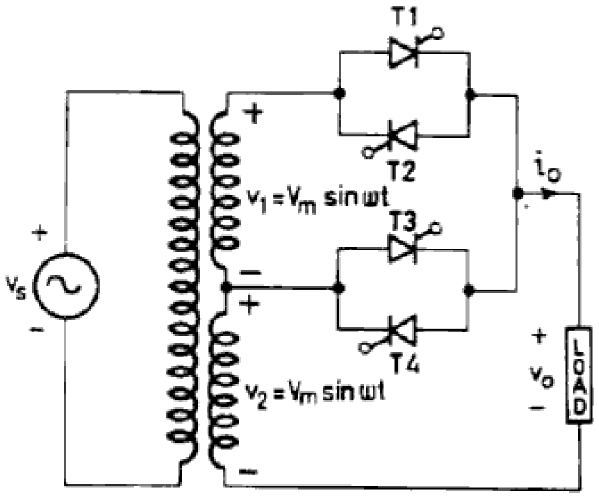
The principle of integral cycle control can be explained by referring to Fig. for a single-phase voltage controller with resistive load. Gate pulses i_{g1}, i_{g2} turn on the thyristors T1, T2 respectively at zero-voltage crossing of the supply voltage. The source energises the load for n (= 3) cycles. When gate pulses are withdrawn, load remains off for m (= 2) cycles. In this manner, process of turn-on and turn-off is repeated for the control of load power. By varying the number of n and m cycles, power delivered to load can be regulated as desired. The waveforms for source voltage v_s, gate pulses and output voltage v_0 are shown in Fig. for $n = 3$ and $m = 2$. Power is delivered to load for n cycles. No power is delivered to load for m cycles. It is the average power in the load that is controlled.

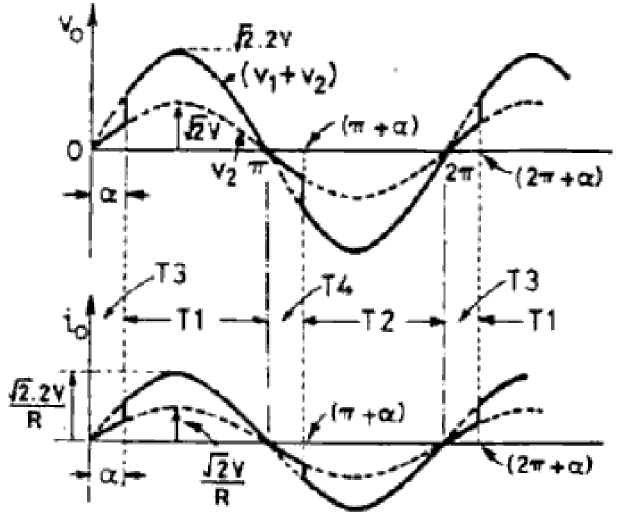
Single phase Voltage Controller with R Load





Two-stage Sequence Control of Voltage Controllers





Cycloconverters

A cyc1oconverter is thus a one-stage frequency changer. Basically, cyc1oconverters are of two types, namely:

(i) step-down cycloconverters and

(ii) step-up cycloconverters .

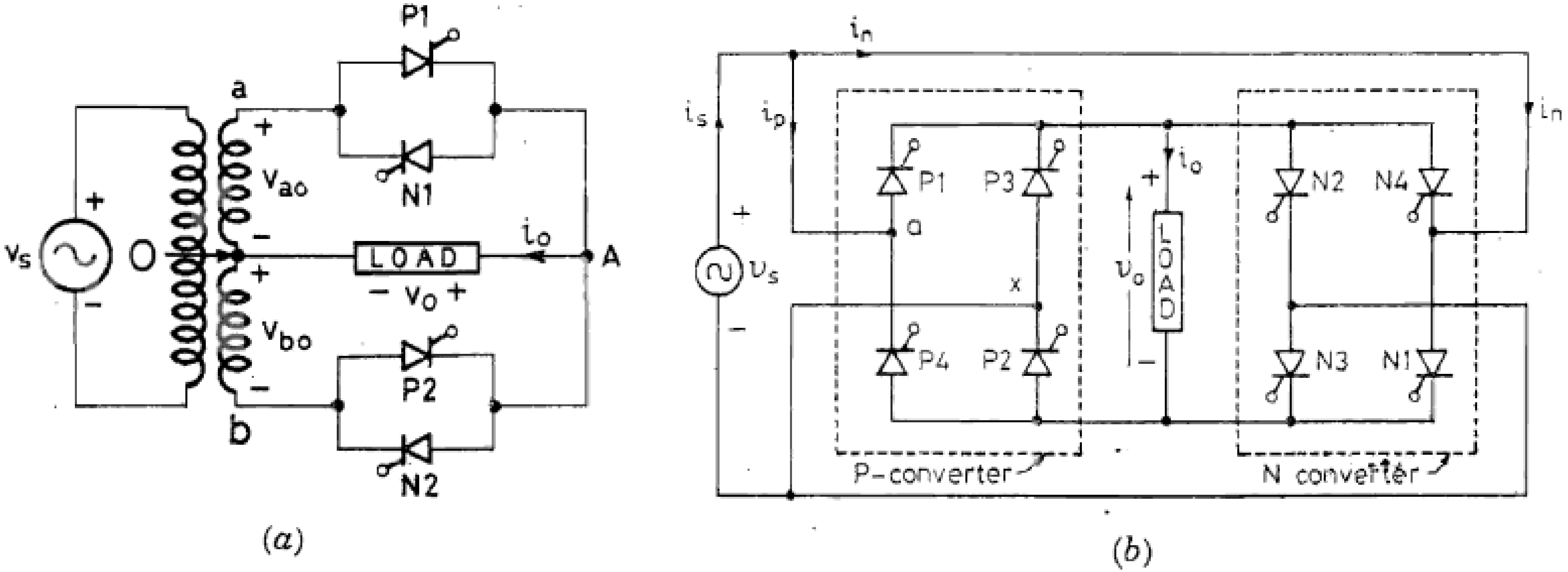


Fig.. Single-phase to single-phase cycloconverter circuit (*a*) mid-point type and (*b*) bridge type.

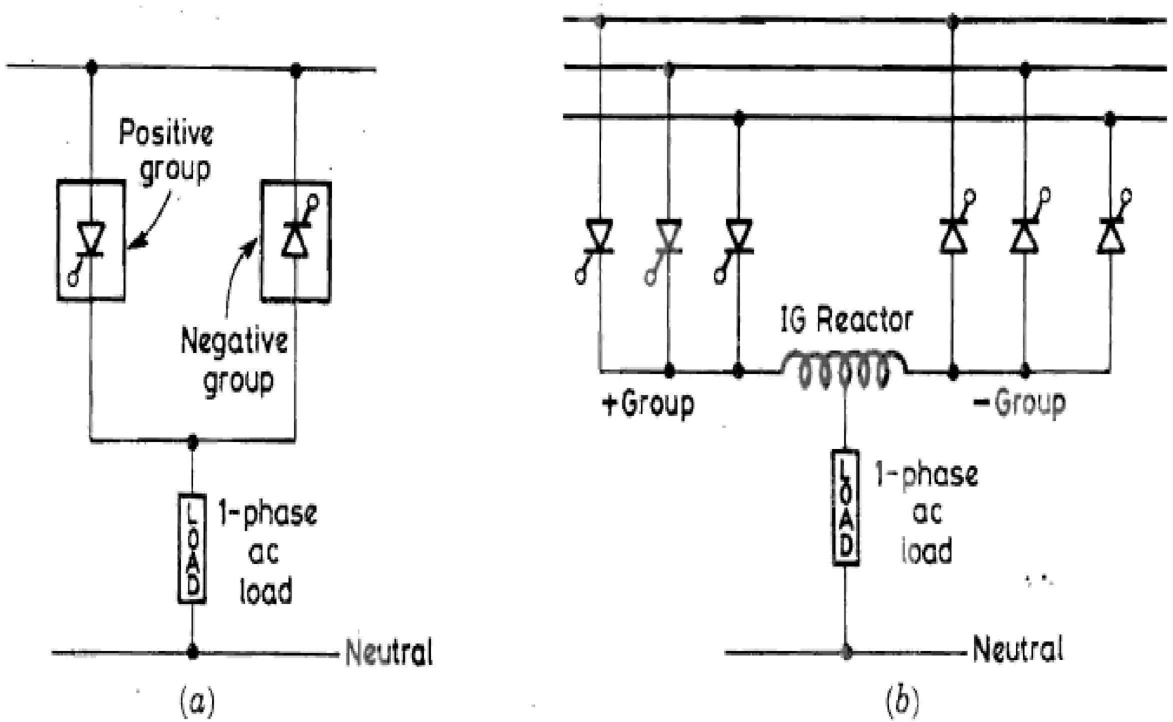


Fig. Three-phase to single-phase cycloconverter (*a*) schematic diagram and (*b*) basic circuit configuration with *IG* reactor.

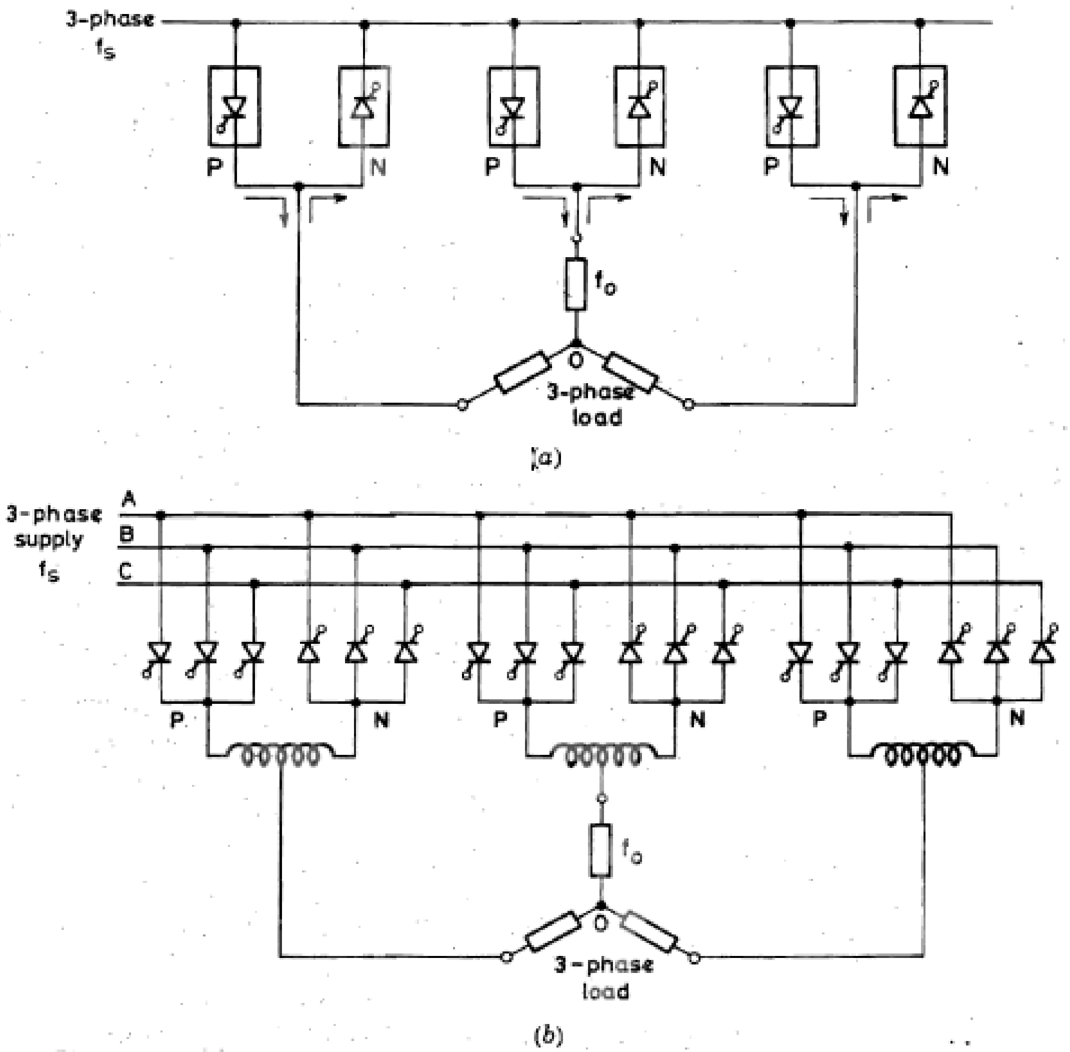
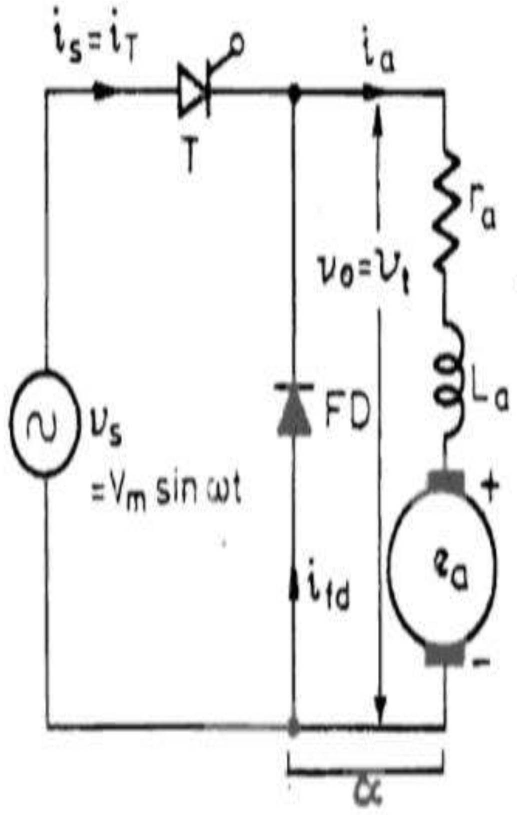
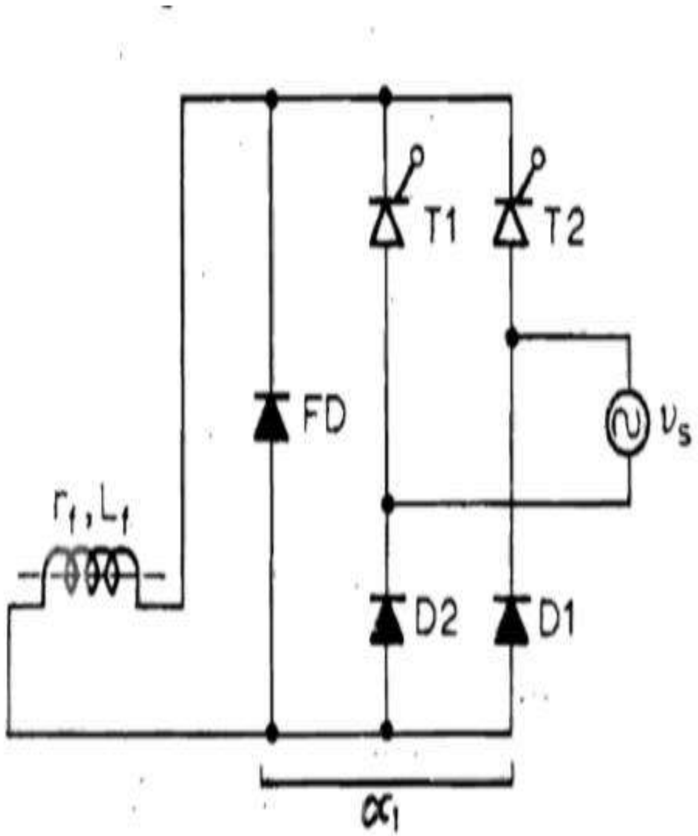
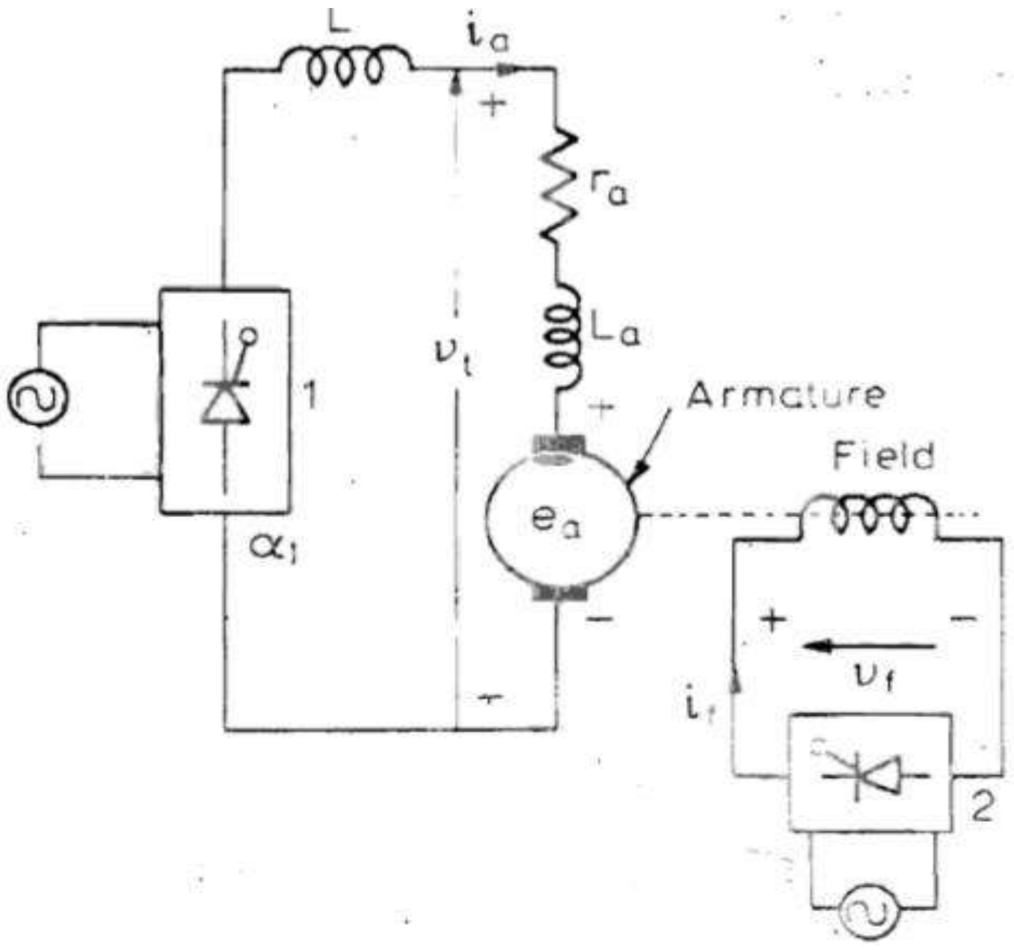


Fig. 3-phase to 3-phase cycloconverter employing 3-phase half-wave circuits (*a*) schematic diagram and (*b*) basic circuit arrangement.

Speed control of a separately-excited dc motor:







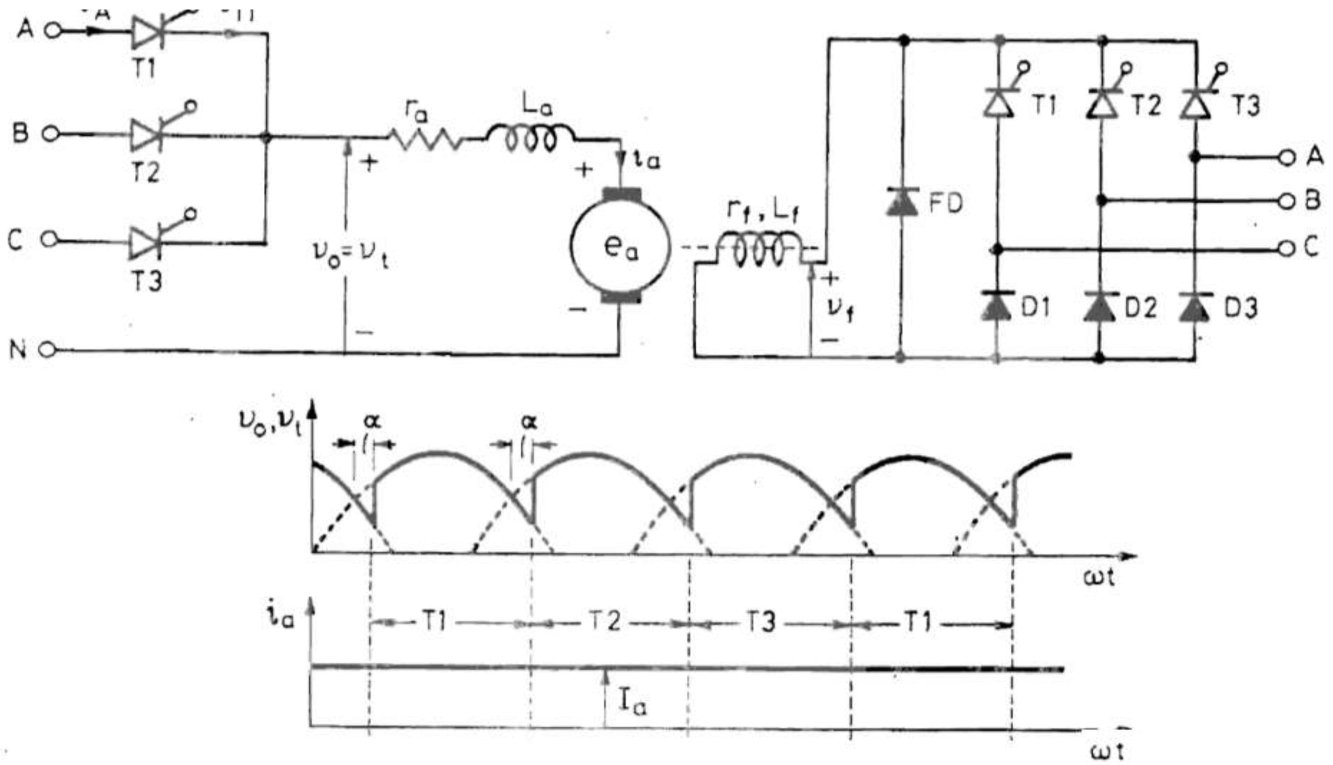
Three-phase half-wave converter drives

For a 3-phase half-wave converter, average value of output voltage or armature terminal voltage,

$$V_0 = V_t = \frac{3V_{ml}}{2\pi} \cos\alpha \quad \text{for } 0 \le \alpha < \pi$$

For thre phase semiconverter, the average value of field voltage,

$$V_f = \frac{3V_{ml}}{2\pi}(1 + \cos\alpha_1) \quad \text{for } 0 \le \alpha_1 \le \pi$$



Three-phase induction motors